V. HYDRODYNAMIC MODELING

V.1. INTRODUCTION

To support the Town with their Comprehensive Wastewater Management Planning (CWMP), an evaluation of tidal flushing has been performed for the coastal embayments within the Town Limits of Chatham. The field data collection and hydrodynamic modeling effort contained in this report, provides the first step towards evaluating the water quality of these estuarine systems, as well as understanding nitrogen loading “thresholds” for each system. The hydrodynamic modeling effort serves as the basis for the total nitrogen (water quality) model, which will incorporate upland nitrogen load, as well as benthic regeneration within bottom sediments. In addition to the tidal flushing evaluation for these estuarine systems, alternatives analyses of tidal flushing improvement strategies have been performed for selected sub-embayments.

Shallow coastal embayments are the initial recipients of freshwater flow and the nutrients they carry. An embayment’s semi-enclosed structure increases the time that nutrients are retained in them before being flushed out to adjacent waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increases the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff and groundwater flows, and to some extent through direct disturbance, i.e. boating, oil and chemical spills, and direct discharges from land and boats. Excess nutrients, especially nitrogen, promote phytoplankton blooms and the growth of epiphytes on eelgrass and attached algae, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

Estuarine water quality is dependent upon nutrient and pollutant loading and the processes that help flush nutrients and pollutants from the estuary (e.g., tides and biological processes). Relatively low nutrient and pollutant loading and efficient tidal flushing are indicators of high water quality. The ability of an estuary to flush nutrients and pollutants is proportional to the volume of water exchanged with a high quality water body (i.e. Nantucket Sound). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For coastal embayments within Pleasant Bay and along the south coast of Chatham, the most important parameters are:

- Tide range
- Inlet configuration
- Estuary size, shape, and depth, and
- Longshore transport of sediment

For this study, Chatham’s estuarine systems have been separated into three general groups: the 1) Stage Harbor System, 2) the South Coast Embayments and the 3) Pleasant Bay Region Embayments (see Figure V-1). Although the three estuarine systems along the south shore (Stage Harbor, Sulphur Springs, and Taylors Pond) exhibit different hydrologic characteristics, ranging from expansive salt marshes to flooded kettle ponds, the tidal forcing for these systems is generated from Nantucket Sound. In contrast, water propagating through the Chatham Harbor/Pleasant Bay system is derived from the Atlantic Ocean.

The south shore of Chatham exhibits a moderate tide range, with a mean range of about 4.5 ft. Since the water elevation difference between Nantucket Sound and each of the estuarine

Figure V-1. Study region for the tidal flushing study including the estuarine systems in the Stage Harbor System (outlined in red), the South Coast Embayments (outlined in yellow), and the Pleasant Bay Region (outlined in blue).

systems is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) through the Stage Harbor system is negligible indicating “well-flushed” systems. In contrast, the tidal attenuation caused by the restrictive channels and marsh plains within the South Coast Embayments of Mill Creek/Taylors Pond is indicative of a “restrictive” system, where tidal flow and the associated flushing are inhibited. Based on the tidal characteristics alone, this might indicate that the Stage Harbor embayments (e.g. Little Mill Pond) are “healthy” relative to the embayments further the west; however, land development in the southeastern portion of Chatham likely provides a substantially higher nutrient load to the Stage Harbor embayments. Consequently, estuarine water quality may be more dependent on nutrient loading than tidal characteristics for these systems.

Within Pleasant Bay, the tide propagating through New Inlet and Chatham Harbor is significantly attenuated by the series of flood tidal shoals within the inlet throat. The mean tide range drops from just under 8 feet in the Atlantic Ocean to around 5 feet at the Chatham Fish Pier. Only minor attenuation occurs between the Fish Pier and Pleasant Bay; however, smaller sub-embayments separated from the main system by culverts exhibit significant additional tidal attenuation. Both Muddy Creek and Frost Fish Creek have mean tide ranges of less than 1 ft.

In addition to tidal forcing characteristics, the regional geomorphology influences flushing characteristics within embayments along the south shore, as well as for the Pleasant Bay system. Shoaling along the south shore of Chatham has caused the opening and closing of several inlets to the Sulphur Springs/Bucks Creek/Cockle Cove Creek system during the past 50 years. In addition, stability issues concerning the Stage Harbor navigation channel required repositioning of the inlet in 1965 as a result of regional shoaling. The most dramatic recent change in local geomorphology occurred in early 1987, when New Inlet formed east of the Chatham Lighthouse. From a tidal flushing and water quality perspective, the resulting increase in tide range within Pleasant Bay of approximately 1 ft caused a substantial improvement of regional tidal exchange.

This report summarizes the development of hydrodynamic models for estuarine systems within the Stage Harbor System, South Coast Embayments, and the Pleasant Bay Region. For each estuarine system, the calibrated model offers an understanding of water movement through the estuary. Tidal flushing information will be utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determine the influence of various methods for improving overall estuarine health.

In general, water quality studies of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

To calibrate the hydrodynamic model, field measurements of water elevations and bathymetry were required. For the Stage Harbor System and the two South Coast Embayments, tide data was acquired within Nantucket Sound (two gauges were installed offshore of Cockle Cove Beach), Oyster Pond, Mill Pond, Little Mill Pond, Sulphur Springs, and Taylors Pond. For the Pleasant Bay Region, tide data was acquired within Pleasant Bay (two gauges were installed at the Chatham Yacht Club in Pleasant Bay), Crows Pond, Ryder Cove, Frost Fish Creek, and Muddy Creek. All 13 temperature-depth recorders (TDRs) were installed for a 30-day period to measure tidal variations through an entire neap-spring cycle. In this manner, attenuation of the tidal signal as it propagates through the various sub-embayments was evaluated accurately. In addition, currents were measured through a tidal cycle within the Stage Harbor and Bassing Harbor systems. These current measurements provided model verification data.

V.2. GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE ESTUARINE SYSTEM

The coast of Chatham is a highly dynamic region, where natural forces continue to reshape the shoreline. As beaches continue to migrate, episodic breaching of the barrier beach system creates new inlets that alter the pathways of water entering the series of local estuaries. Storm-driven inlet formation often leads to hydraulically efficient estuarine systems, where seawater exchanges more rapidly with water inside the estuary. However, this episodic inlet formation is balanced by the gradual wave-driven migration of the barrier beach separating the estuaries from the ocean. As beaches elongate, the inlet channels to the estuaries often become long, sinuous, and hydraulically inefficient. Periodically, overwash from storm events will erode the barrier beach enough at a point to allow again the formation of a new inlet. It is then possible that the new inlet will stabilize and become the main inlet for the system, while the old inlet eventually fills in. Several examples of this process along the Massachusetts coast include Allen’s Pond (Westport), New Inlet/Chatham Harbor/Pleasant Bay (Chatham), and Nauset inlet (Orleans). In addition, alterations to the sediment transport patterns in the Cockle Cove/Ridgevale Beach region have altered the tidal inlets to both the Sulphur Springs and Cockle Cove Creek estuaries during the past 50 years.

In addition to natural phenomena affecting estuarine hydrodynamics, man-made alterations have impacted tidal exchange in Chatham’s coastal embayments. Examples of anthropogenic modifications range from repositioning of the Stage Harbor inlet in the 1960’s to the construction of culverts under Route 28 that restrict tidal exchange between two sub-embayments and Pleasant Bay. Manmade coastal/estuarine structures consist of jetties, groins, and dikes. Many of these structures were utilized to maintain the position of navigation channels; however, alterations to longshore sediment transport patterns may have influenced the stability of inlets to the region’s estuaries. Also, dikes and weirs were constructed in the upper portions of some estuarine bodies to prohibit tidal exchange. In these cases, tidelands were reclaimed for agricultural purposes (primarily cranberry bogs).

Although man has modified much of the Chatham coastline, most of the large-scale changes to the estuarine systems have been caused by nature. For example, the 1987 breach of Nauset Beach caused a substantial increase in the tide range of Pleasant Bay (an increase of approximately 1.0 feet). In addition to increasing the tide range, this natural alteration to the system caused a substantial increase in tidal exchange with the Atlantic Ocean and improved the water quality in the upper portions of the estuary. Most of the manmade modifications to coastal embayments have caused small changes to overall estuarine health. While the culverts restricting tidal flow under Route 28 have had a negative influence on water quality within Muddy and Frost Fish Creeks, this influence is minor relative to natural large-scale changes.

V.2.1 Stage Harbor

As a result of regional littoral drift patterns, the location of the Stage Harbor entrance channel, as well as other channels influencing system circulation, have been altered over the past 100 years. Natural migration of the Nauset Beach system and Monomoy Island/Shoals has caused extensive periods of channel shoaling. Following the 1987 breach of Nauset Beach, abrupt changes to the circulation and sediment transport patterns within Chatham Harbor and Pleasant Bay occurred. Although alterations to the sediment supply to the southern portion of the Nauset Beach and Monomoy Island system have occurred less dramatically, landward migration of the southern remnants of Nauset Beach from the 1846 breach influenced circulation patterns within Chatham and Stage Harbors.

Figure V-2, from Geise (1988) illustrates the historic shoreline change of the Nauset Beach system over the 200-year period between 1770 and 1970. Following the 1846 breach, the barrier north of the inlet extended southward and the barrier beach south of Morris Island reattached to Morris Island (Figure V-2, between 1850 and 1950). By 1940, the same general form of 1800 had returned. Southward growth of Nauset Beach until it reached south of Morris Island and the separation of the southern barrier from Morris Island (forming Monomoy Island) occurred after 1940. This process continued until the 1987 breach of Nauset Beach initiated the cyclical pattern in a similar fashion as the 1846 breach.

Periodic breaching of the spit connecting Morris Island to Monomoy Island has caused local shifts in sediment transport patterns and associated shoaling in the vicinity of the Stage Harbor entrance. Prior to the mid-1960s, the inlet to Stage Harbor was located along the western edge of Morris Island, approximately 2,000 feet east of its present location. According to Geise (1988), Harding Beach was artificially breached in 1965 to create the inlet that exists today. As part of the inlet relocation project, the U.S. Army Corps of Engineers constructed a sand dike between the new inlet and Morris Island.

The proximity of the pre-1965 Stage Harbor entrance to Morris Island may have made it difficult to maintain a stable navigation channel once the spit south of Morris Island separated and formed Monomoy Island. In addition, migration of the barrier island remnants following the 1846 breach caused the separation of Amos Point from the mainland, forming Morris Island. Figures V-3, V-4, and V-5 illustrate the changes in the Morris Island region between 1893 and 1943. Prior to 1910, the Morris Island dike was protected from the Atlantic Ocean by Nauset Beach. As the barrier beach remnant migrated landward, it eventually joined the mainland. By 1917 (Figure V-3), natural overwash of the Morris Island dike created a hydraulic connection between Stage and Chatham Harbors. In 1943, the connection between Stage and Chatham Harbors allows circulation at all stages of the tide. By the 1960's, the Morris Island dike was constructed, blocking the connection between the two harbors. The 1994 aerial photograph (Figure V-6) shows the present form of the Stage Harbor system, with the pre-1965 inlet location and the previous connection to Chatham Harbor shown.

The Morris Island dike will continue to prohibit tidal exchange between Stage and Chatham Harbors for the foreseeable future. In addition, the 1965 location of the Stage Harbor inlet likely will remain in its present location, which will require maintenance dredging on an as-needed basis to ensure safe navigation. Although a series of geomorphic and man-induced changes have occurred within the Stage Harbor estuary during the past 100 years, the existing system appears to be in a state of equilibrium.

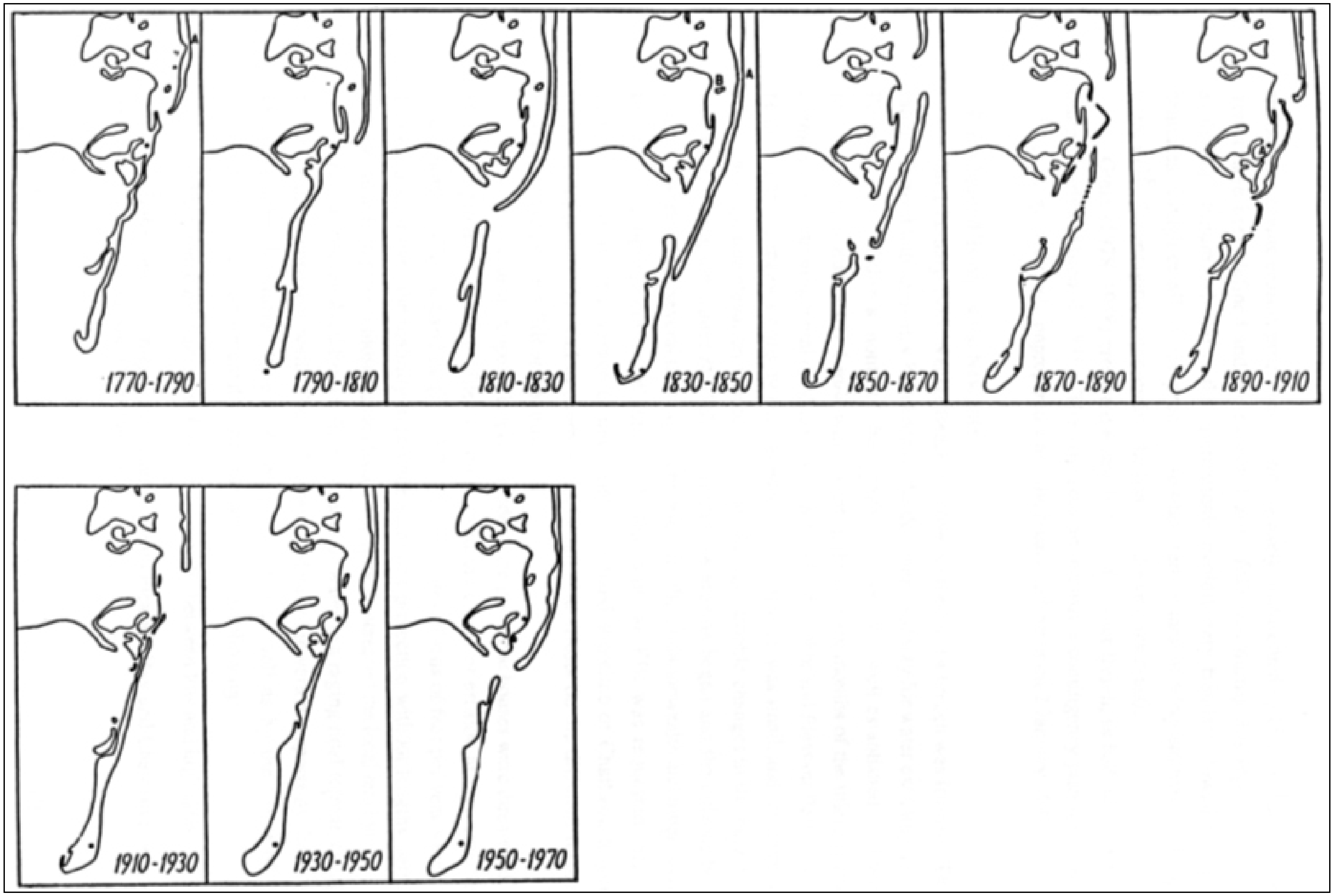

Figure V-2. Historical changes in the Nauset Beach-Monomoy barrier system illustrated by generalized 20-year diagrams from 1770-1790 to 1950-1970 (from Geise, 1987).

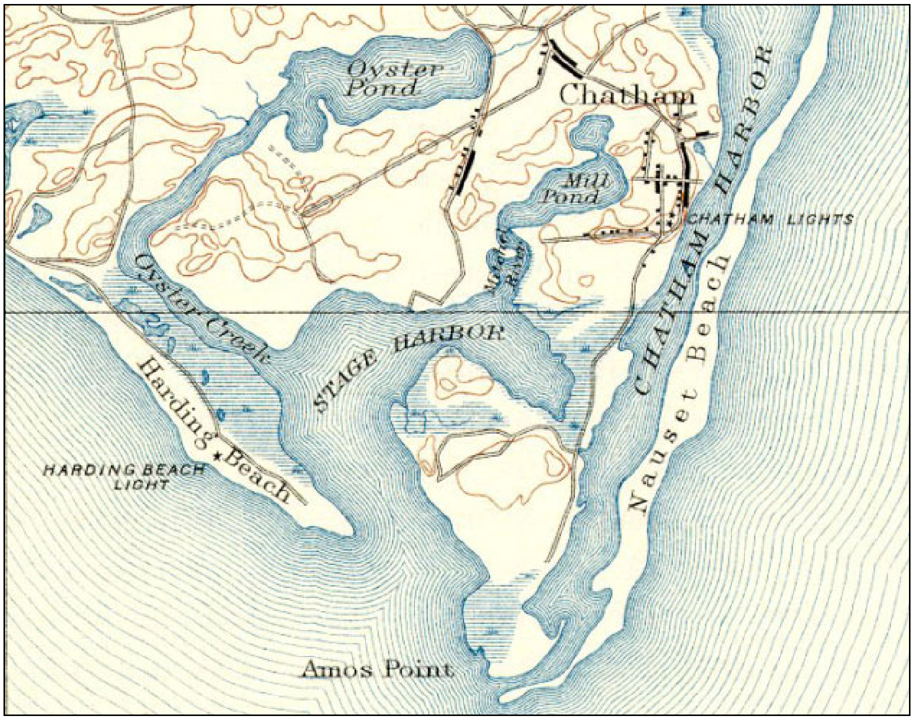

Figure V-3. Topographic map from 1893 showing the old Stage Harbor inlet location and a roadway to Morris Island/Amos Point.

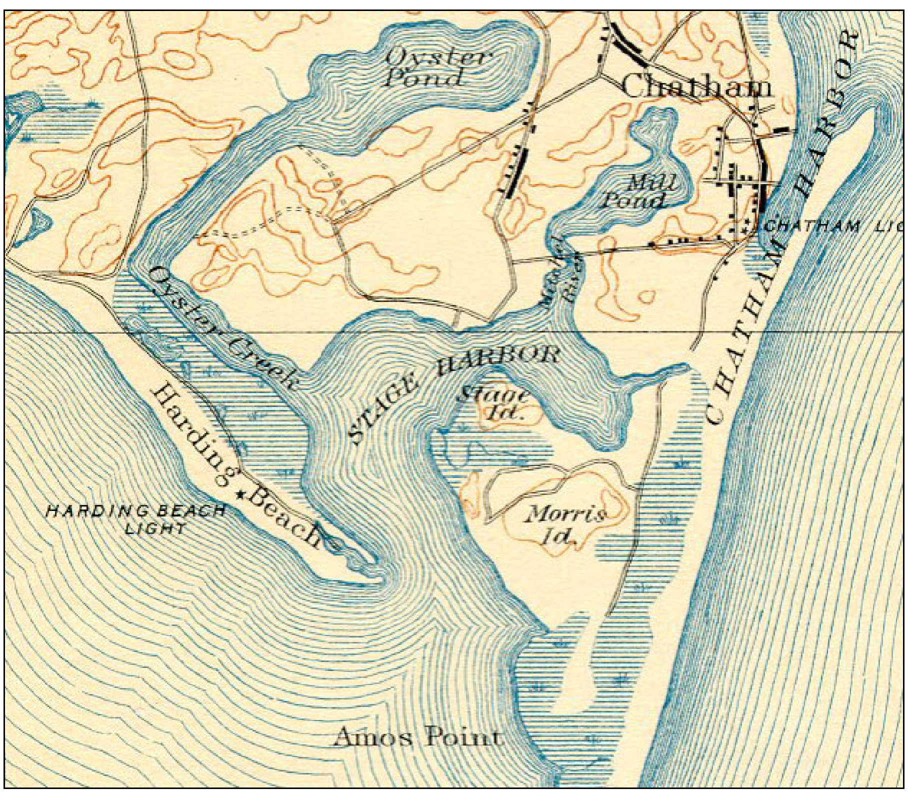

Figure V-4. Topographic map from 1917 showing the region of overwash between Stage and Chatham Harbors.

Figure V-5. Topographic map from 1943 showing the hydraulic connection between Stage and Chatham Harbors.

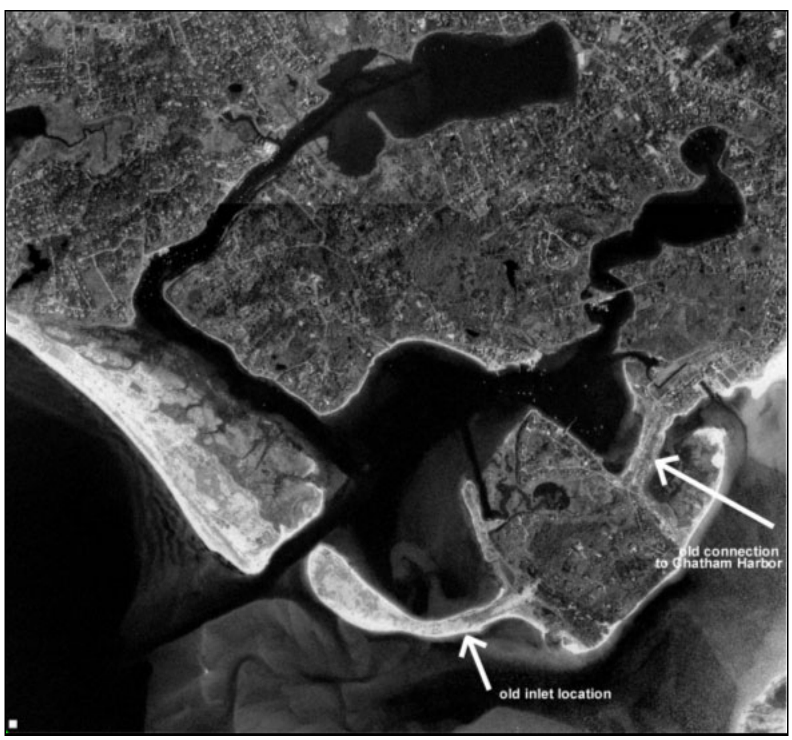

Figure V-6. Aerial photograph from 1994 showing the present system and the location of historic inlet features.

V.2.2 South Coast Embayments

A series of groins were constructed along the south coast of Harwich and Chatham during the 1950's. These structures primarily were constructed to the west of the Mill Creek inlet as a means of trapping littoral drift to stabilize the shoreline. Although these structures often succeeded in protecting beaches updrift (to the west) of the groin fields, downdrift beaches were often starved of sediments. As illustrated in the 1943 topographic map (Figure V-7), a natural sand spit extended from the Mill Creek inlet to the east approximately 1,500 feet, forming Cockle Cove. Taylors Pond/Mill Creek, Cockle Cove Creek (referred to as Bucks Creek on the map), and Sulphur Springs were all connected directly to Cockle Cove.

Following the construction of the groin field in the 1950's, the spit forming Cockle Cove began migrating shoreward as the sediment source for this feature disappeared. The spit was overwashed during storm events, and formed a series of shore parallel bars in the remnants of Cockle Cove. An aerial photograph from the 1950's (Figure V-8) illustrates the series of migratory sandbars. In addition, overwash processes closed the Buck's Creek entrance, forcing tidal waters to enter Sulphur Springs via Cockle Cove Creek.

By the late 1970's, the barrier spit remnants had attached to the shoreline and the three estuarine systems each had a direct connection with Nantucket Sound. Figures V-9, V-10, and V-11 show a series of oblique aerial photographs of the Taylors Pond, Cockle Cove Creek, and Sulphur Springs systems taken in 1979. The Taylors Pond estuary is similar in form to the system that exists today. Figure V-10 illustrates a barrier dividing Cockle Cove and Buck's Creeks, maintaining the hydraulic separation of these estuaries. By this time period, the "training" groins to the east of the Buck's Creek entrance had been constructed. Training groins are used to direct tidal currents from an inlet away from the shoreline in order to limit shoreline erosion and the natural migration of this inlet (Figure V-11).

The 1994 aerial photograph (Figure V-12) illustrates the general form of the estuaries as they appear today. The Cockle Cove Creek inlet has closed and the connection to the Buck's Creek system was reestablished. Although it is possible that a storm could breach the barrier beach to the east of the Cockle Cove Beach parking lot and reopen the Cockle Cove Creek entrance, ongoing beach nourishment efforts along Cockle Cove Beach should continue to stabilize the beach in its present location. Since the sediment supply to beaches in this region is relatively small, it is likely that the system will retain its general form of one inlet servicing both Cockle Cove Creek and the Buck's Creek/Sulphur Springs system.

V.2.3 Pleasant Bay Region

Many of the regional barrier beach systems in Chatham formed after a rise in relative sea level during the Holocene. Approximately 5,000 years before present, relative sea-level was about 15-20 feet below the level existing today. As relative sea level increased over the past 5,000 years, continued erosion of the cliffs in Orleans, Eastham, Wellfleet, and Truro provided sediment to downdrift beaches, modifying the form of the nearshore area. Nauset Beach formed from the erosion of these cliffs and the predominant southerly littoral drift. As relative sea-level continued to increase, the bluffs along the eastern shore of Cape Cod continued to erode and the shoreline moved to the west. Nauset Beach has migrated to the west as a result of episodic overwash events in a process referred to as barrier beach rollover. The "Halloween Storm" of 1991 was an example of this rollover process, where the barrier beach was steepened and large volumes of sand were deposited into Pleasant Bay.

The formation of New Inlet in 1987 altered the hydrodynamics within the Pleasant Bay Estuary. As a result of the inlet, the tide range in Pleasant Bay has increased by approximately 1 ft, with a corresponding improvement to tidal flushing within the northern portions of the estuary. The inlet continues migrating south and Nauset Beach will return to a morphology similar to the pre-breach form. This pattern of inlet formation and southerly growth of Nauset Beach is cyclical. The two most recent breaches through the Nauset barrier occurred in 1846 east of Allen Point and 1987 east of the Chatham Lighthouse. The anticipated cyclical behavior of the inlet system is based on the work of Geise (1988) who described the historical 1846 breach and the subsequent re-formation of Nauset Beach during the next 140 years. Figure V-2 illustrates the cyclical behavior of the Chatham Harbor/Pleasant Bay system between 1770 and 1970.

Following the 1987 breach, the beach system returned to its 1846 form and the cycle started again. As Nauset Beach continues to grow in a southerly direction, the estuarine system becomes less hydraulically efficient, and the phase lag between high tide in the Atlantic Ocean and high tide in the estuary becomes greater. Once a small breach forms during storm overwash conditions, the difference in water elevations between the ocean and the estuary will quickly scour a more efficient channel that will eventually widen to an inlet. For example, the 1987 breach occurred on January 2nd; within one month the breach was well established and within four months the inlet was nearly one mile wide.

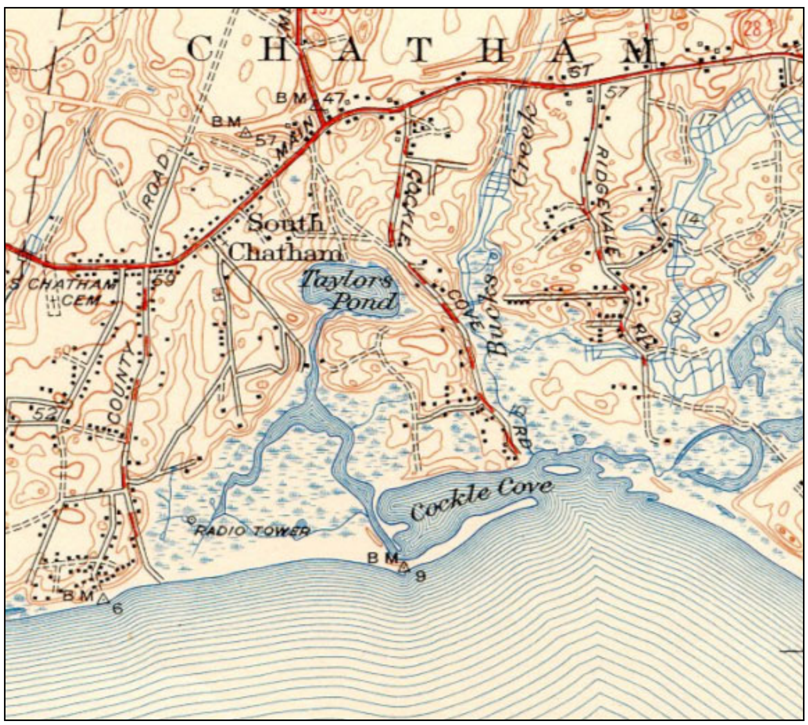

Figure V-7. Topographic map from 1943 showing the Taylors Pond, Cockle Cove Creek (designated as Bucks Creek on this map), Sulphur Springs, and the sand spit forming Cockle Cove.

Figure V-8. Aerial photograph from the 1950's showing the shore parallel bars along Cockle Cove Beach and the location of the inlet servicing the Sulphur Springs/Buck's Creek/Cockle Cove Creek system.

Over the past 13 years, littoral drift (wave-driven transport along the outer coast) has caused several shifts in the inlet position of the Chatham Harbor system. Immediately following the 1987 breach, a two-inlet system existed, where Chatham Harbor was connected directly to the Atlantic Ocean east of Chatham Lighthouse and the historic inlet south of Morris Island remained open. By the early 1990's the more efficient inlet across from the lighthouse had captured the tidal prism and the southern inlet had closed. The primary navigation channel migrated to the south and ran along the beach fronting the lighthouse. Between 1999 and 2001, a second navigation channel opened across the swash platform to the north. Each of these changes has altered the pathway of tidal waters entering the Chatham Harbor/Pleasant Bay estuary, as well as the tide range and flushing characteristics of the system.

As Nauset Beach continues its southerly growth, the inlet naturally will become less efficient. Although this process will be gradual over the next 50-to-100 years, the Town of Chatham should consider the impact of this cyclic inlet behavior on estuarine flushing and the associated water quality. For this reason, the previous flushing study of the Pleasant Bay (ACI, 1997) evaluated existing conditions in 1997 and the less hydraulically efficient pre-breach conditions. The flushing analysis performed for the present study also incorporates existing conditions and the 'worst-case' pre-breach conditions.

Figure V-9. Oblique aerial photograph from 1979 showing the Taylors Pond and Mill Creek system, with the groin field established updrift of the Mill Creek entrance.

Figure V-10. Oblique aerial photograph from 1979 showing the inlet to Cockle Cove Creek, as well as the barrier separating the Buck's Creek and Cockle Cove Creek systems.

Figure V-11. Oblique aerial photograph from 1979 showing the inlet to Buck's Creek, as well as the barrier separating the Buck's Creek and Cockle Cove Creek systems.

Figure V-12. Aerial photograph from 1994 showing the Taylors Pond, Cockle Cove Creek, and Sulphur Springs estuarine systems as they exist today.

V.2.3.1 Bassing Harbor, Ryder Cove, and Crows Pond

Although the formation of New Inlet in 1987 increased the tide range in all of the sub-embayments surrounding Pleasant Bay, alterations to flow patterns were relatively minor in Bassing Harbor, Ryder Cove, and Crows Pond. The shoals at the entrance of Bassing Harbor have continued to shift over the past decade; however, the cross-sectional area of the channel appears to be stable. Therefore, tidal flushing has not been affected by the minor inlet shoaling.

V.2.3.2 Muddy Creek and Frost Fish Creek

Construction of a roadway along the Route 28 corridor has inhibited tidal exchange between Pleasant Bay and two sub-embayments within Chatham (Muddy Creek and Frost Fish Creek). For Muddy Creek, structures intended to control water levels have been in use since the turn of the century (Duncanson, 2000), and have included, at different times, tide gates, a dam, and the present earthwork structure and culvert under Route 28. In their present condition, the culverts at both Frost Fish Creek and Muddy Creek cause more than a three-fold decrease in the tide range. The location of these culverts is shown on Figure V-13.

The two culverts running under Route 28 at Muddy Creek each have a height of approximately 2.6 feet and a width of 3.7 feet. Since the surface area of Muddy Creek is relatively large, these culverts are not of sufficient size to allow complete tidal exchange between Pleasant Bay into Muddy Creek. This poor tidal exchange is likely responsible for the water quality concerns for the Muddy Creek system. Alternatives to improve tidal flushing and water quality within Muddy Creek are discussed in Section VI.

Two types of flow control structures exist at Frost Fish Creek. First, three partially-blocked 1.5 feet diameter culverts run under Route 28. Approximately 100 feet upstream of these culverts, a single large culvert and a dilapidated weir structure maintain the Creek level well above the mean tide elevation in adjoining Ryder Cove. Since the weir structure likely maintained Frost Fish Creek as a freshwater system, the culverts were adequate for handling the freshwater outflow from the Frost Fish Creek watershed. Following removal of the weir boards, Frost Fish Creek became a salt marsh system with a tide range of less than 0.5 feet. Based on an interpretation of watersheds delineated by the Cape Cod Commission, the freshwater recharge into Frost Fish Creek represents approximately 20% of the flow through the Route 28 culverts. Similar to Muddy Creek, the size of the culverts limits tidal exchange with Ryder Cove and the rest of the Pleasant Bay estuary. The poor tidal exchange is likely responsible for the water quality concerns within Frost Fish Creek. Alternatives to improve tidal flushing in Frost Fish Creek are discussed in Section VI.

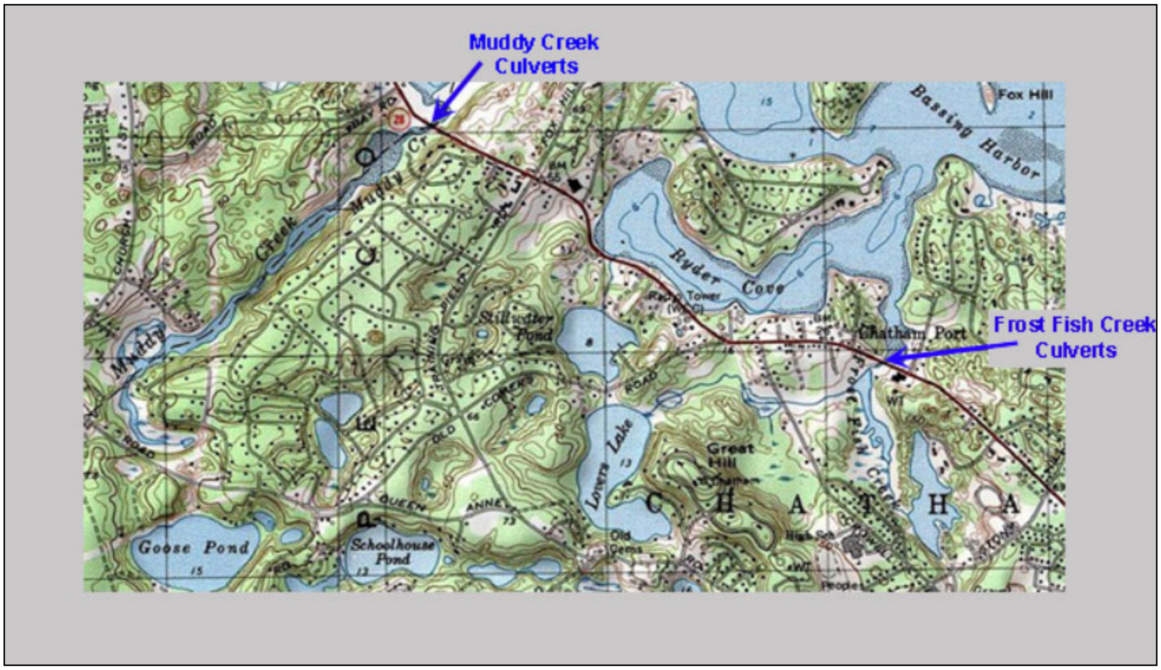

Figure V-13. Topographic map indicating the location of the Muddy Creek and Frost Fish Creek culverts inhibiting tidal exchange with the Pleasant Bay estuary.

V.3 FIELD DATA COLLECTION AND ANALYSIS

A precise description of embayment geometries and hydrodynamic forcing processes is required for the development of numerical models. To support the hydrodynamic and water quality modeling effort in the Stage Harbor, South Coast, and Pleasant Bay regions, tidal currents, water elevation variations, and bathymetry of the embayments were measured. For the purposes of this study, the Stage Harbor geographic region consists of Stage Harbor, Oyster Pond River, Oyster Pond, Mitchell River, Mill Pond, Little Mill Pond (Figure V-14). The South Coast Embayments consist of Cockle Cove Creek, Bucks Creek, Sulphur Springs, Mill Creek, and Taylors Pond (Figure V-14). The following embayments are grouped together in the Pleasant Bay region in this study: Bassing Harbor, Crows Pond, Ryder Cove, Frost Fish Creek, and Muddy Creek (Figure V-15). Cross-channel current measurements were surveyed through a complete tidal cycle at three locations in each system. Tidal elevation measurements within selected embayments were used for both forcing conditions and to evaluate tidal attenuation through each estuarine system. Bathymetry data was collected in regions where the coverage of previous work lacked accuracy and/or detail necessary for evaluation of tidal hydrodynamics. In the Stage Harbor and South Coast regions, bathymetric surveys were conducted in Stage Harbor, Oyster Pond, Mitchell River, Mill Pond, Bucks Creek, and Mill Creek. Bathymetry was collected in Bassing Harbor, Ryder Cove, Crows Pond, Frost Fish Creek, and Muddy Creek for the Pleasant Bay region. The depth measurements were supplemented by bathymetry from past surveys for use in the construction of computational grids for each modeled system.

V.3.1 Data Acquisition

V.3.1.1 Water Elevation

Changes in water surface elevation were measured using internal recording tide gages. These tide gages were installed on fixed platforms (such as pier pilings) to record changes in water pressure over time. Variations in the water surface can be due to tides, wind set-up, or other low frequency oscillations of the sea surface. The tide gages were installed in 6 locations in the Stage Harbor and South Coast regions (Figure V-14) in late July 2000 and recovered in late August 2000. The gages were re-deployed in 5 locations in the Pleasant Bay region (Figure V-15) in late August 2000 and recovered in late September 2000. Data records span at least 29 days to yield an adequate time period for resolving the primary tidal constituents at each site.

The Temperature-Depth Recorders (TDR) used to measure tide levels for this study were the Brancker TG-205, Coastal Leasing Macrotide, and Global Water WL-14 instruments. Temperature and pressure data were recorded at 10-minute intervals, with each 10-minute observation resulting from an average of 60 1-second pressure measurements. Each of these instruments use strain gage transducers to sense variations in pressure, with resolution on the order of 1 cm (0.39 inches) head of water. The proper calibration of each gage was verified prior to installation to assure accuracy.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. The Global Water WL- 14 gage is vented to atmosphere, so it records pressure from the water column above the instrument only, and therefore does not need atmospheric correction. The atmospheric pressure record used to correct the other TDR data was derived by subtracting the Global Water WL-14 pressure time series from a second gauge deployed at the same location, which recorded the sum of water column and atmospheric pressure. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gage). This density assumption is appropriate for even Muddy Creek and Frost Fish Creek where brackish water (salinity less than 15-20 ppt) is possible, because density variations are small (at most 2.5% between fresh water and sea water), and the gages were positioned in relatively shallow water (less than 3ft). All TDR gages were surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum.

The result from each gage is a time series representing the variations in water surface elevation relative to NGVD29 (National Geodetic Vertical Datum of 1929). NGVD29 is a standard fixed vertical reference. Though it is based on the 1929 mean sea level at several stations in the US, there is no consistent relationship between NGVD29 and mean sea level at different locations. FiguresV-16 toV-18 present the water levels at each gage location shown in FiguresV-14 andV-15. The only irregularity experienced during both deployments of the TDRs in Chatham was for the gage in Muddy Creek. Failure of the primary battery caused the unit to stop recording 29.8 days into the deployment, as can be seen in the early termination of the plot in Figure V-18 for Muddy Creek. Data quality is not impacted by primary battery failure. Because the Muddy Creek data record is longer than 29 days, the data record is sufficient to perform a harmonic analysis of its significant tidal constituents.

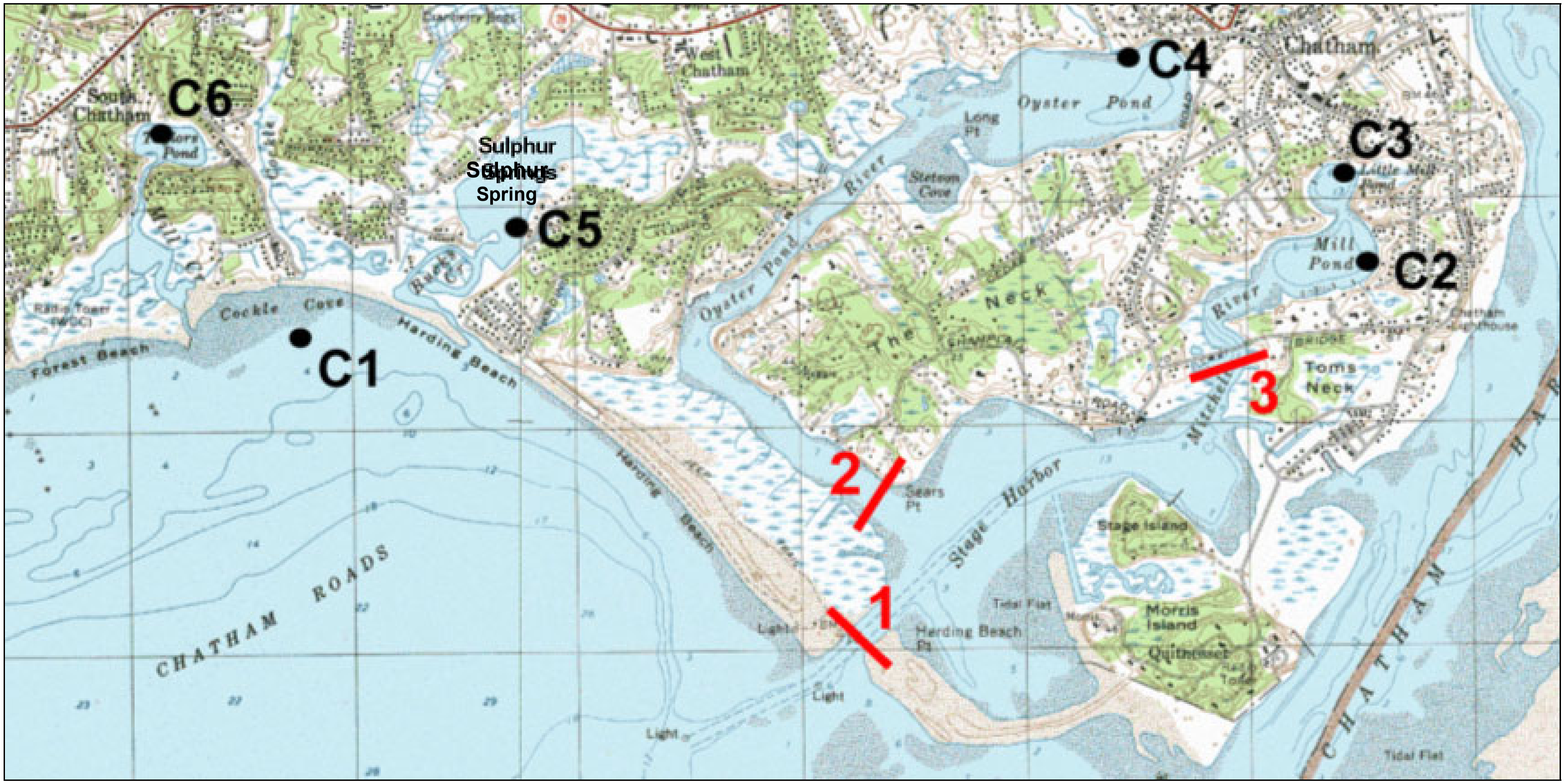

Figure V-14. Tide gage and ADCP transect locations in the Stage Harbor region (C1-C6 are tide gage locations and heavy red lines 1-3 are ADCP transects)

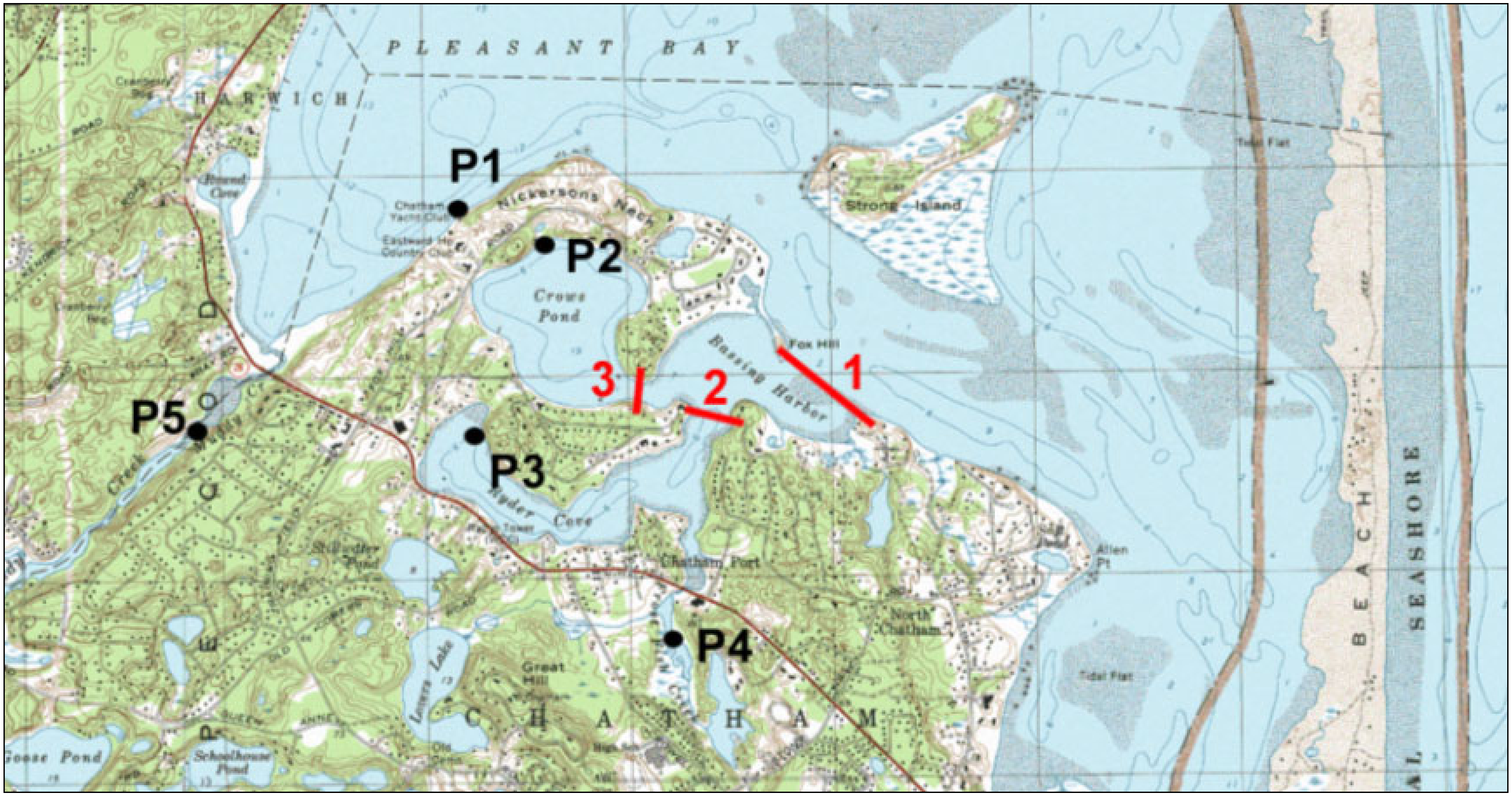

Figure V-15. Tide gage and ADCP transect locations in the Pleasant Bay region (P1-P5 are tide gage locations and heavy red lines 1-3 are ADCP transects).

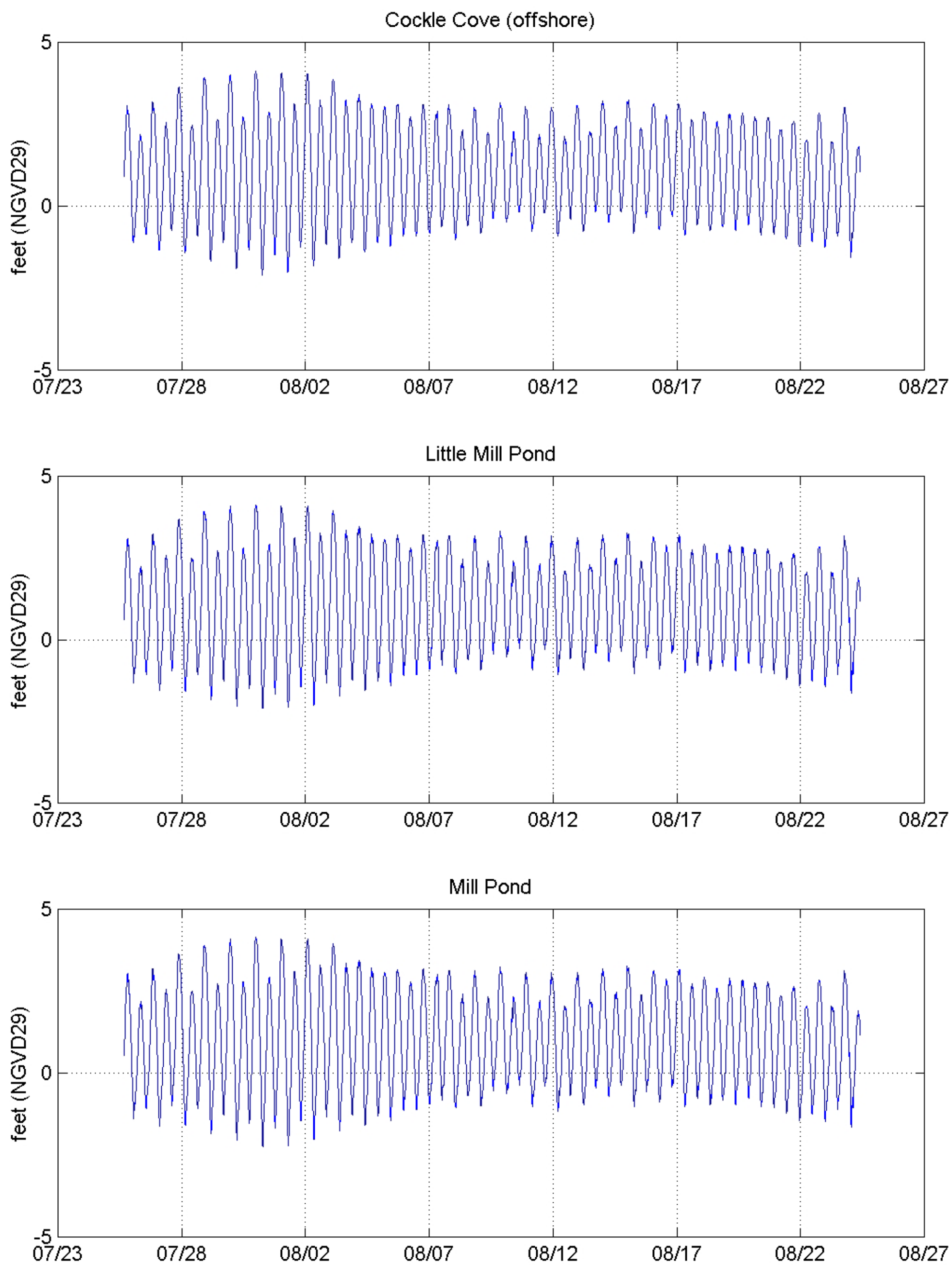

Figure V-16. Tidal elevation observations for offshore Cockle Cove Beach (location C1 of Figure V-14), Little Mill Pond (location C2), and Mill Pond (location C3).

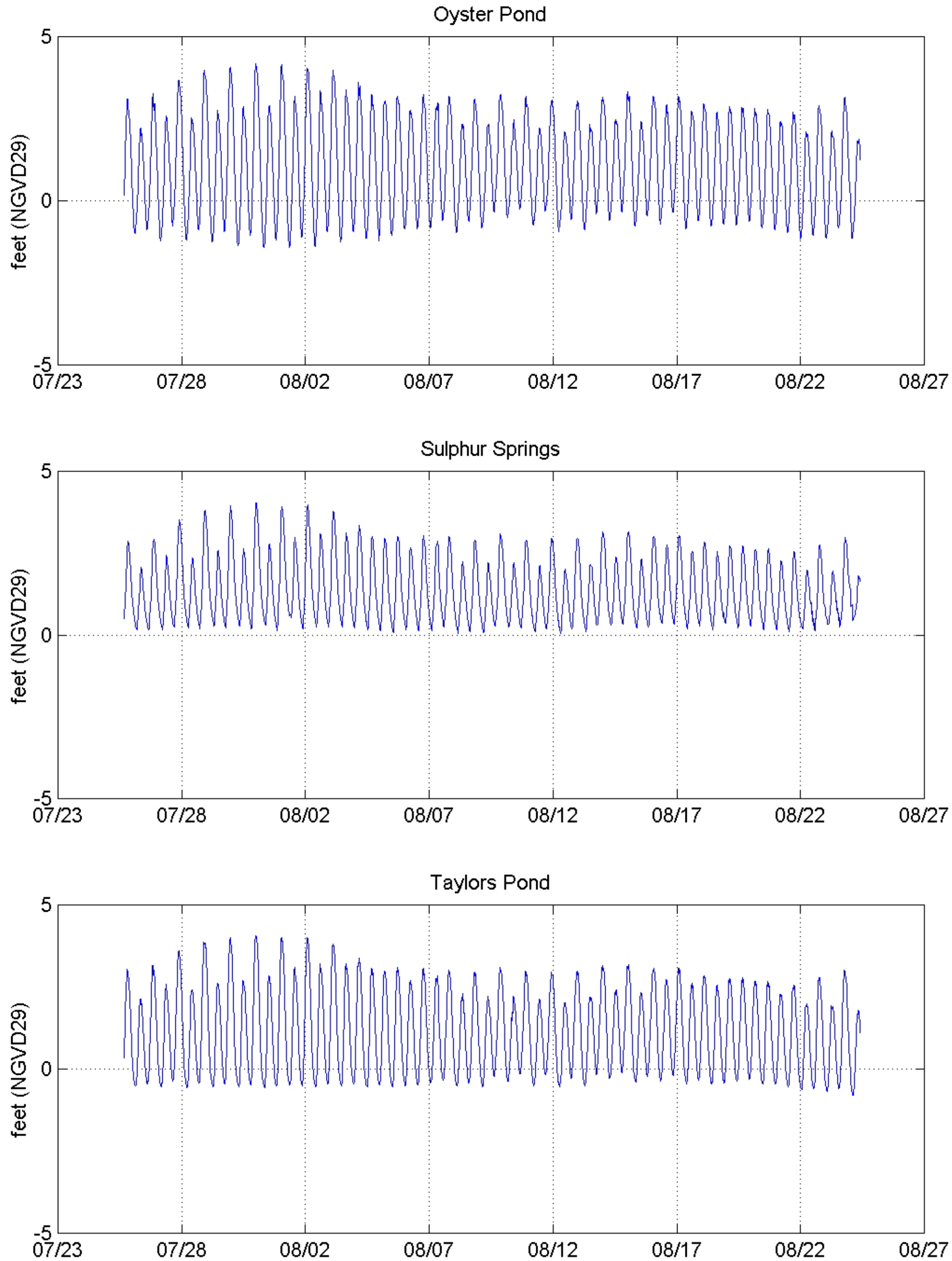

Figure V-17. Tidal elevation observations for Oyster Pond (location C4 of Figure V-14), Sulphur Springs (location C5), and Taylors Pond (location C6).

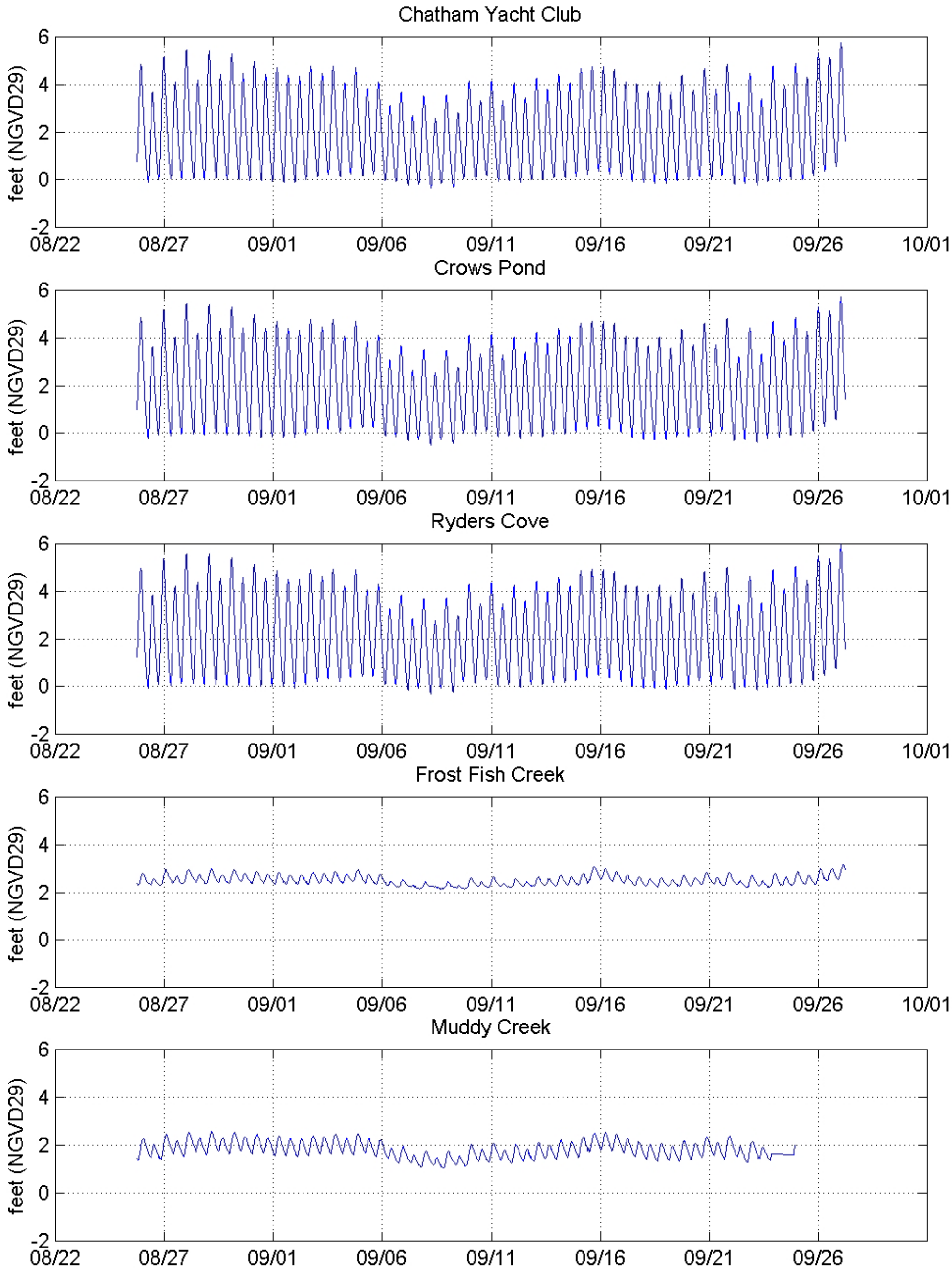

Figure V-18. Tidal elevation observations for Chatham Yacht Club (location P1 of Figure V-15), Crows Pond (location P2), Ryder Cove (location P3), Frost Fish Creek (location P4), Muddy Creek (location P5).

V.3.1.2 Bathymetry

V.3.1.2.1 Stage Harbor and South Coast Embayments

Bathymetry, or depth, of Stage Harbor, Mill Pond, Oyster Pond, and Mill Creek was measured during field surveys in August 2000. The surveys were completed using a small vessel equipped with a precision fathometer interfaced to a differential GPS receiver. The fathometer has a depth resolution of approximately 0.1 foot and the differential GPS provides x-y position measurements accurate to approximately 1-3 feet. Digital data output from both the echosounder and GPS were logged to a laptop computer.

GPS positions and echosounder measurements were merged to produce data sets consisting of water depth as a function of x-y horizontal position (in Massachusetts Mainland State Plane, 1983). The data were combined with water surface elevations to obtain the vertical elevation of the bottom (z) relative to the NGVD 1929 vertical datum (NGVD29). The resulting xyz files were input to mapping software to calculate depth contours for the system shown in Figures V-19 andV-20. Where necessary, bathymetry collected by Applied Coastal was supplemented by existing data from NOAA collected in 1956. The 1956 NOAA data were not used in southern Stage Harbor, where significant changes have occurred as a result of the relocation of the harbor inlet in 1965.

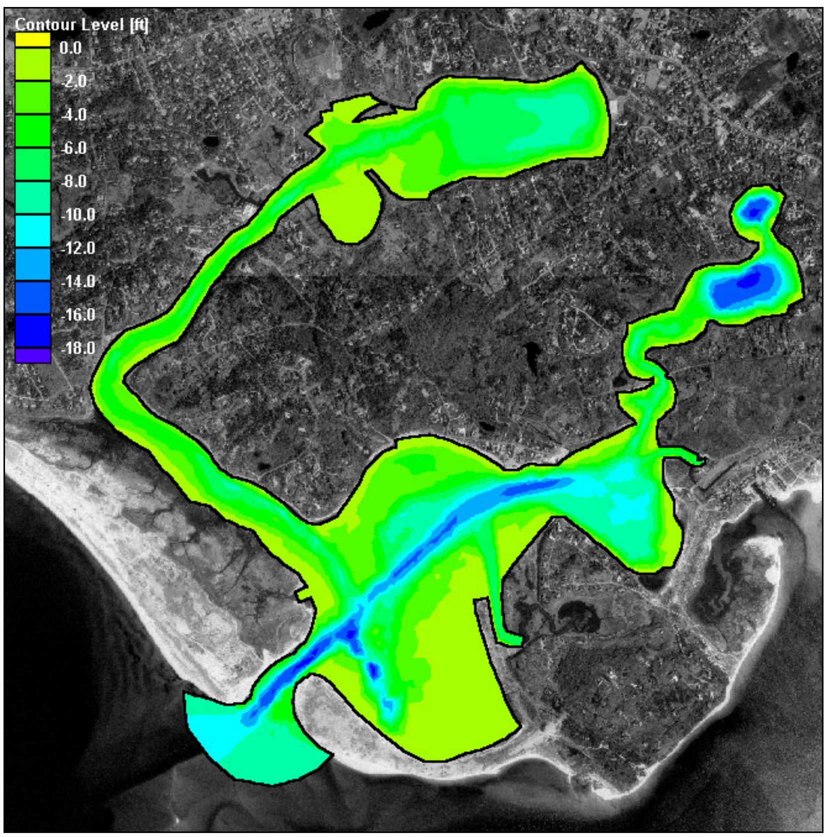

Figure V-19. Depth contour plots of the numerical grid for the Stage Harbor system at 2-foot contour intervals relative to NGVD29 (August 2000 survey, supplemented with 1956 NOAA data in the upper reaches).

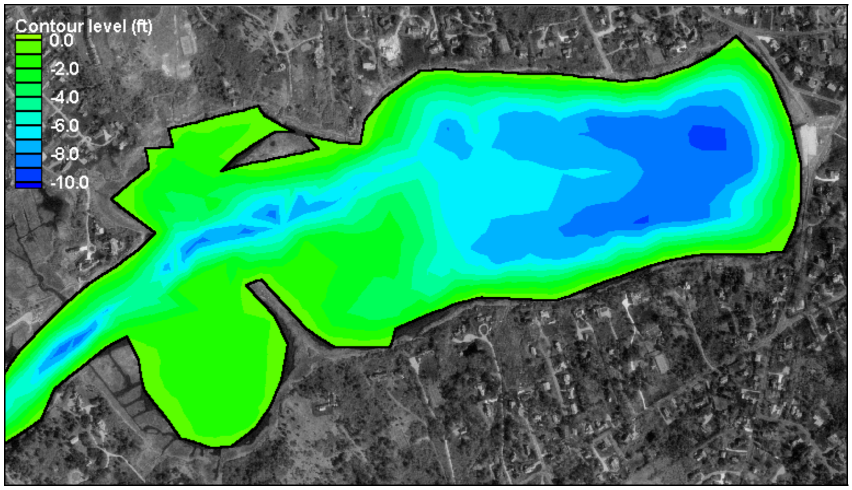

Figure V-20. Depth contour plots of the numerical grid for Oyster Pond (Stage Harbor system) region at 2-foot contour intervals relative to NGVD29 (August 2000 survey, supplemented with 1956 NOAA data).

Bathymetry shown in Figure V-21 for Taylors Pond and Figure V-22 for Sulphur Springs were collected by Applied Science Associates, Inc. in 1998. Applied Coastal took additional measurements in the Sulphur Springs/Buck Creek's system on August 23, 2000 with standard surveying equipment. Elevation measurements were surveyed across seven, shore perpendicular transects at the mouth of Bucks Creek using an automatic digital level sighting on a stadia rod. These measurements were adjusted to NGVD29 from local benchmarks.

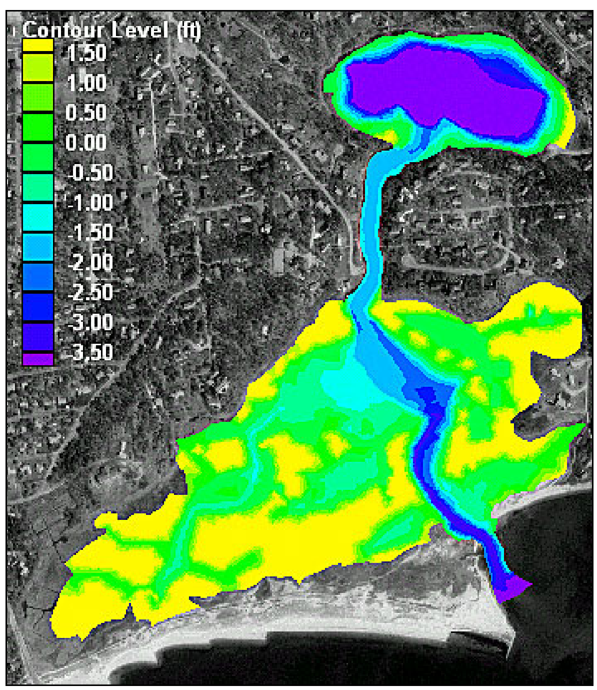

Figure V-21. Depth contour plot of the numerical grid for Taylors Pond and Mill Creek at 0.5 foot contour intervals relative to NGVD29 (August 2000 survey). The yellow to light green indicates marsh plain elevation, and the darker blues to indigo indicate the depth of the creeks and pond basin.

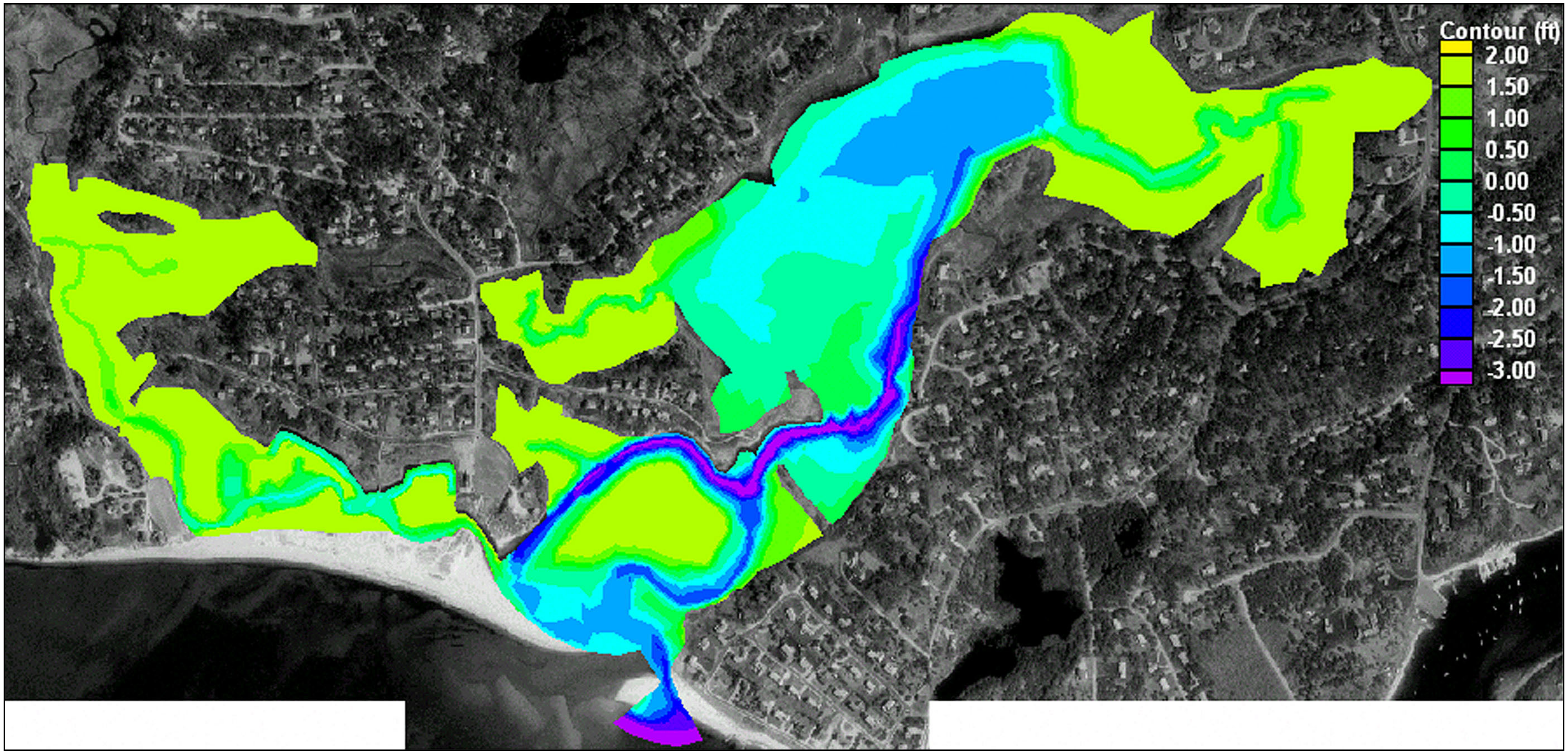

Figure V-22. Depth contour plot of the numerical grid for Sulphur Springs, Bucks Creek, and Cockle Cove Creek at 0.5-foot contour intervals relative to NGVD29 (August 2000 survey). The light green indicates marsh plain elevation, and the darker blues to indigo indicate the depth of the pond basin and creeks.

V.3.1.2.2 Pleasant Bay Region

In the Bassing Harbor system, bathymetry data were collected in September 2000 using an Acoustic Doppler Current Profiler (ADCP) with bottom tracking capability. Measurements were taken in Bassing Harbor, Ryder Cove, lower Frost Fish Creek, and Crows Pond to supplement existing bathymetry collected by Aubrey Consulting, Inc. in 1997. The surveys were conducted in the same manner as the current measurements (described in Section 3), on a small vessel with the ADCP transducer rigidly mounted and a differential GPS collecting position data. In addition to velocity, the bottom tracking process of the ADCP calculates the depth of the seabed below the unit.

The depths were merged with water surface elevations to obtain the vertical elevation of the bottom (z) relative to the NGVD29 vertical datum. The vertical elevations were combined with the x-y horizontal positions from the GPS (Massachusetts Mainland State Plane, 1983), producing xyz files that were input to mapping software. Depth contours for the Bassing Harbor system are depicted in Figure V-23.

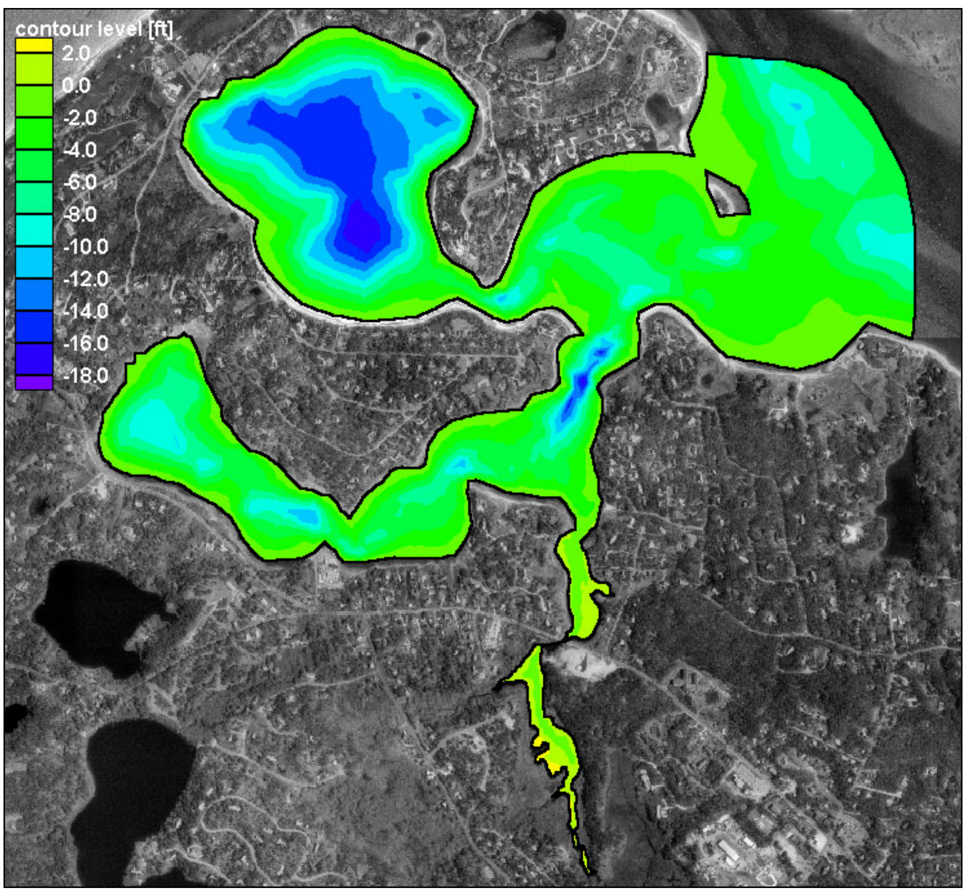

Figure V-23. Depth contour plot of the numerical grid for Bassing Harbor, Ryder Cove, Crows Pond, and Frost Fish Creek at 2-foot contour intervals relative to NGVD29 (September 2000 survey).

Bathymetry was collected in Upper Frost Fish Creek and Muddy Creek from a 16-foot canoe with a hand held differential GPS and stadia rod. Transects were measured cross-creek spaced at 200-300 foot intervals along the length of the creek. Water elevation and GPS x-y positions were simultaneously recorded by hand every 30-50 feet across each transect. The x-y positions were transferred to Massachusetts Mainland State Plane coordinates, and elevation data were combined with tidal water surface elevations to obtain the vertical elevation of the bottom (z) relative to NGVD29. Depth contours were produced for these two systems by the input of the xyz files into mapping software (Figure V-24 and V-25).

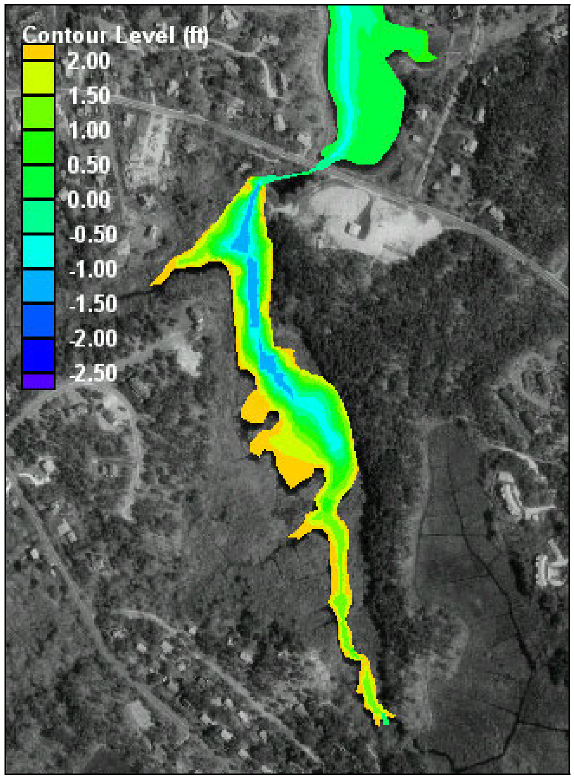

Figure V-24. Depth contour plot of the numerical grid for Frost Fish Creek at 0.5 foot contour intervals relative to NGVD29 (September 2000 survey).

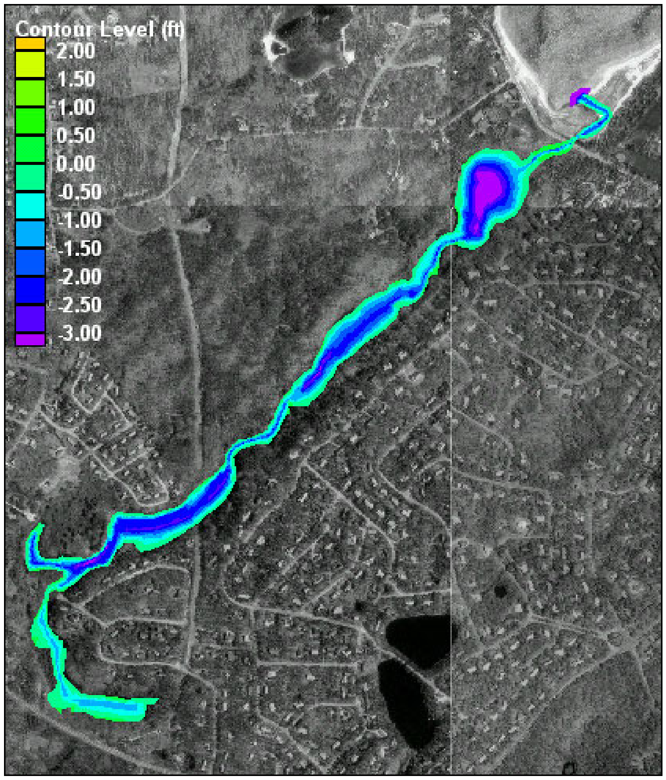

Figure V-25. Depth contour plot of the numerical grid for Muddy Creek at 0.5 foot contour intervals relative to NGVD29 (September 2000 survey).

V.3.1.3 Current Measurements

The measurements were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated a pre-defined set of transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for an approximate 12.6-hour duration to ensure measurements over the entire tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

Measurements were obtained with a BroadBand 1200 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments (RDI) of San Diego, CA. The ADCP was mounted to a specially constructed mast, which was rigidly attached to the rail of the survey vessel. The ADCP was oriented to look directly downward into the water column, with the sensors located 9 inches below the water surface. The mounting technique assured no flow disturbance due to vessel wake.

The ADCP emits individual acoustic pulses from four angled (at 20° from the vertical) transducers in the instrument. The instrument then listens to the backscattered echoes from discrete depth layers in the water column. The difference in time between the emitted pulses and the returned echoes, reflected from ambient sound scatters (plankton, debris, sediment, etc.), is the time delay. BroadBand ADCPs measure the change in travel times from successive pulses. As particles move further away from the transducers sound takes longer to travel back and forth. The change in travel time, or propagation delay, corresponds to a change in distance between the transducer and the particle, due to a Doppler shift. The propagation delay, the time lag between emitted pulses, and the speed of sound in water are used to compute the velocity of the particle relative to the transducer. By combining the velocity components for at least three of the four directional beams, the current velocities are transformed using the unit's internal compass readings to an orthogonal earth coordinate system in terms of east, north, and vertical components of current velocity.

Vertical structure of the currents is obtained using a technique called 'range-gating'. Received echoes are divided into successive segments (gates) based on discrete time intervals of pulse emissions. The velocity measurements for each gate are averaged over a specified depth range to produce a single velocity at the specified depth interval ('bin'). A velocity profile is composed of measurements in successive vertical bins.

The collection of accurate current data with an ADCP requires the removal of the speed of the transducer (mounted to the vessel) from the estimates of current velocity. 'Bottom tracking' is the strongest echo return from the emission of an additional, longer pulse to simultaneously measure the velocity of the transducer relative to the bottom. Bottom tracking allows the ADCP to record absolute versus relative velocities beneath the transducer. In addition, the accuracy of the current measurements can be compromised by random errors (or noise) inherent to this technique. Improvements in the accuracy of the measurement for each bin are achieved by averaging several velocity measurements together in time. These averaged results are termed 'ensembles'; the more pings used in the average, the lower the standard deviation of the random error.

For this study, the standard deviation (or accuracy) of current estimates (resulting from an ensemble average of 8 individual pulses) was approximately 0.30 ft/sec. Each ensemble took approximately 5-6 seconds to collect. Averaging parameters resulted in a horizontal resolution of approximately 13 feet along the transect line. For example, Stage Harbor Inlet was approximately 350 feet wide, resulting in approximately 25-30 independent velocity profiles per transect. The vertical resolution was set to 0.82 ft, or one velocity observation per every 9.8 inches of water depth. The first measurement bin was centered 2.8 feet from the surface, allowing for the transducer draft as well as an appropriate blanking distance between the transducer and the first measurement.

Position information was collected by Hypack, an integrated navigation software package running on a PC computer, linked to a differential GPS. The position data were read from the device in the WGS-84 coordinate system, and transformed to NAD 1983 Massachusetts Mainland State Plane coordinates. Position updates were available every 1 second. Clock synchronization between the GPS and ADCP laptop computers allowed each ADCP ensemble to be assigned an accurate GPS position during post-processing.

V.3.1.3.1 Description of Survey Technique

Stage Harbor System

Current measurements were collected by the ADCP as the vessel navigated repeatedly a series of three (3) pre-defined transect lines through the survey area (Figure V-14). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 06:48 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 19:36 hours (EDT), for a survey duration of approximately 12.8 hours on August 16, 2000. Each individual transect line was surveyed through a time span of approximately 12.4 hours, for example, transect Line 1 was crossed initially at 06:48 hours and crossed for the final cycle at 19:10 hours.

The transect lines were numbered sequentially 1 through 3, and run in ascending order. These lines were designed to measure as accurately as possible the volume flux through the inlets during a complete tidal cycle. Line 1 ran across the throat of the Stage Harbor Inlet in a southeast-to-northwest direction. Line 2 ran southeast-to-northeast at the throat of Oyster Pond River Inlet, and line 3 ran across the mouth of Mill Pond on the south side of the bridge beginning along the bank on the west flank of the entrance running from southwest-to-northeast along the bridge.

Bassing Harbor System

A series of three (3) pre-defined transect lines in the Bassing Harbor study area were surveyed (Figure V-15) in the same manner. The first cycle was begun at 06:29 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 18:54 hours (EDT), for a survey duration of approximately 12.5 hours on September 1, 2000. Each individual transect line was surveyed through a time span of approximately 12.2 hours.

Line 1 ran across the throat of Bassing Harbor Inlet in a north-to-south direction. Line 2 ran east-to-west at the mouth of Ryder Cove, and line 3 ran across the mouth of Crows Pond from south-to-north.

V.3.1.3.2 Data Processing Techniques

- Data processing consisted of the following:
- Convert raw ADCP (binary) files to engineering units
- Merge ADCP vertical profile data with GPS position data
- QA/QC procedures to verify the accuracy of both ADCP and position data
- Manipulate the ADCP data to calculate spatial averages and cross section discharge values

The data files were converted from raw binary format to engineering ASCII values using RDI's BBLIST conversion program. The command set for this conversion process is described in greater detail in the RDI ADCP manual, and consists of developing a user-defined output file format, through which all conversions are defined.

The output data file from this procedure consists of multiple ensemble data 'packets'. The ensemble 'packet' consists of a single line containing the time of the profile, the ensemble number, and the measured water temperature (measured by the ADCP's internal temperature sensor) followed by consecutive rows and columns of the profile data. Each row of profile data corresponds to one bin, or depth layer, with succeeding columns representing east and north components of velocity, error velocity, speed, direction, echo amplitudes (for 4 beams), and correlation magnitudes (for 4 beams). Each ensemble, collected approximately every 5-6 seconds, has 30 rows corresponding to each discrete depth layer, starting at 2.8 feet. A single data file consists of multiple ensembles, as few as 25-30 to as many as 100. A single data file was recorded for each transect.

The next step in the processing was the assignment of an accurate x-y position pair to each ensemble. This was accomplished using the time stamp of both the ADCP data file and the position data file. Prior to the survey, the clocks used for each system were synchronized to assure this operation was valid. The procedure finds the time of each ADCP ensemble, then searches the position data file for the nearest corresponding time. When the nearest time is found, subject to a 'neighborhood' limit of 1 second, the x-y pair for that time is assigned to the ADCP ensemble. This method produces some inaccuracies; however for this survey the error in position definition was less than approximately 3.5 feet (calculated as vessel speed of 2 knots times the neighborhood value of 1 second for this survey). If no time is found within 1 second of the ADCP time, then a position is calculated using the ADCP bottom track velocity for that ensemble, and the time interval between ensembles.

Once each ensemble was assigned a valid x-y position, the data were reduced to calculate vertical averages as well as total discharge. A mean value of each east and north component of velocity is calculated for each vertical profile. These component mean values are then used to determine the mean speed and mean direction.

The total discharge time series represents the total volumetric flow through a waterway cross-section over the duration of the tidal cycle. Discharge calculations were performed on velocity components normal and tangential to the transect azimuth, which in most cases was perpendicular to the channel axis. To determine accurately the discharge normal to the channel cross-section (i.e. along-stream), the east and north velocity components were rotated into normal (along-stream) and tangential (cross-stream) components. Only the along-stream component was used to calculate total discharge.

The total discharge through a channel, Q_t, is computed as the summation of the individual ensemble flows, which is in turn the summation of the product of bin velocity, V, and bin cross sectional area, A, using the velocity measurements through the complete water column, expressed as:

$$Q_t = \sum_{j=1}^{m}\sum_{i=1}^{n}\left(V_i A_i\right)_j$$

where the cross sectional area is the bin depth times the lateral (cross-stream) distance from the previous ensemble profile. The summation occurs over *i*, where *i* represents each individual bin measurement from 1 to *n*, with 1 representing the top (surface) bin and *n* representing the deepest good (near-bottom) bin, and then over *j*, where *j* represents the ensembles along the survey transect.

Data recorded for the bottom-most bins in the water column can be contaminated by side lobe reflections from the transducer. At times, the measurements can be invalid. Validity of the bottom bin measurements is determined by comparing the standard deviation of bottom values to the standard deviation of mid-column measurements. If the standard deviation at the bottom was more than twice the standard deviation of mid-column measurements, the bottom bin was discarded from the discharge calculation. If the bottom value was within the limits defined by adjacent measurements, the value was included in the calculation.

The total discharge calculations assume a linear extrapolation of velocity from the surface to the first measurement bin (centered at 3.2 feet). Since the ADCP cannot directly measure the surface velocity, the surface layer current is set to current in the first measured depth layer. The same linear assumption was applied to bottom bins when the bin measurement was declared invalid; that is, the bottom bin value was assumed equivalent to the overlying bin velocity value.

V.3.2 Discussion of Results

Analyses of the tide and bathymetric data provided insight into the hydrodynamic characteristics of each system. Harmonic analysis of the tidal time series produced tidal amplitude and phase of the major tidal constituents, and provided assessments of hydrodynamic ‘efficiency’ of each system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

V.3.2.1 Stage Harbor System and South Coast Embayments

V.3.2.1.1 Tidal Harmonic Analysis

Figure V-16 shows the tidal elevation for the period July 23 through August 27, 2000 at three locations: offshore Cockle Cove Beach in Nantucket Sound (Location C1), Little Mill Pond (Location C2), and Mill Pond (Location C3). The curves have a predominant 12.42-hour variation around the lunar semi-diurnal (twice-a-day), or M_2, tidal constituent. There was also a strong modulation of the lunar and solar tides, resulting in the familiar spring-neap fortnightly cycle. The spring (maximum) tide range was approximately 6 feet, and occurred on July 30. The neap (or minimum) tide range was 2.2 feet, occurring August 13th.

Tidal elevations are shown for the next three locations in Figure V-17: Oyster Pond (Location C4), Sulphur Springs (Locations C5), Taylors Pond (Locations C6). Oyster Pond closely follows the tidal elevations for the previous three locations. Sulphur Springs and Taylors Pond drain to Nantucket Sound through shallow, narrow meandering creeks (Bucks Creek and Mill Creek, respectively). The tide signals in these two estuaries, as compared to the offshore signal, show the effects of significant frictional damping. The frictional damping is indicated by the substantial reduction in tide range between the offshore gage and locations within each estuarine system.

Harmonic analyses were performed on the time series from each gage location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-1 presents the amplitudes of the eight largest tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.79 feet in Nantucket Sound (offshore Cockle Cove). The range of the M_2 tide is twice the amplitude, or 3.58 feet. The diurnal tides, K_1 and O_1, possess amplitudes of approximately 0.3 feet. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, strongly contribute with amplitudes of 0.19 feet and 0.52 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 and M_6 have a very small amplitude in the offshore gage (about 0.13 feet and 0.08 feet. The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon.

Table V-1. Tidal Constituents, Stage Harbor and South Coast Embayments of Chatham, July-August 2000								
	Amplitude (feet)							
Constituent	M2	M4	M6	S2	N2	K1	O1	Msf
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Offshore	1.79	0.13	0.08	0.19	0.52	0.35	0.29	0.14
Mill Pond	1.86	0.09	0.08	0.19	0.52	0.35	0.29	0.14
Little Mill Pond	1.85	0.09	0.08	0.19	0.52	0.35	0.29	0.12
Oyster Pond	1.80	0.07	0.04	0.18	0.47	0.35	0.30	0.13
Sulphur Springs	1.17	0.21	0.02	0.12	0.25	0.29	0.27	0.16
Taylors Pond	1.60	0.11	0.04	0.14	0.40	0.32	0.29	0.18

The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-26.

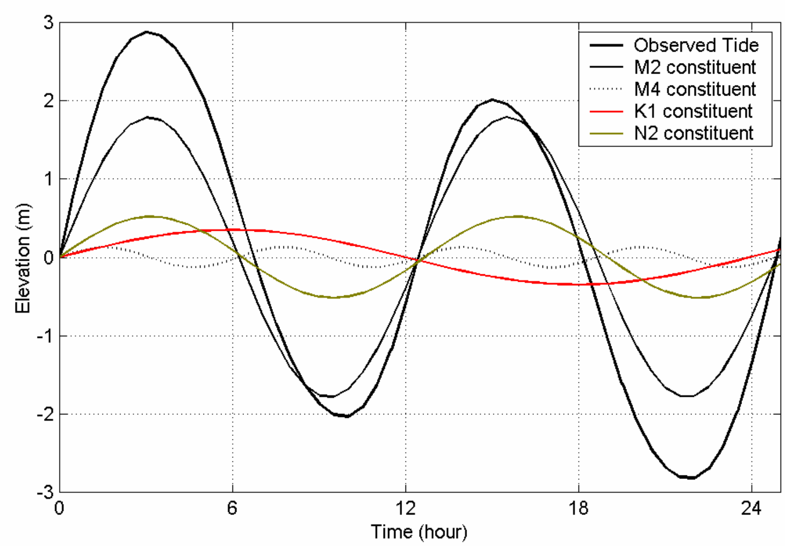

Figure V-26. Example of observed astronomical tide as the sum of its primary constituents. Constituents for offshore Cockle Cove Beach were used in this example.

Table V-1 also shows how the constituents vary as the tide propagates into the estuaries. Note the reduction in the M_2 amplitude between Nantucket Sound and the upper reaches of Sulphur Springs and Taylors Pond. The loss of amplitude with distance from the inlet is described as tidal attenuation. Frictional mechanisms dissipate tidal flow energy, resulting in a reduction of the height of the tide. Usually, frictional damping is most evident as a decrease in the amplitude of M_2 constituent. A portion of the energy lost from the M_2 tide is transferred to higher harmonics (i.e., the M_4 and M_6), and is observed as an increase in amplitude of these constituents over the length of an estuary. This is seen in the tide at Sulphur Springs, where there is a significant growth of the M_4 constituent from offshore. In contrast, an apparent reduction in the M_2 constituent occurs as the tide propagates from Nantucket Sound in the Stage Harbor System (especially into Mill and Little Mill Ponds). This growth in the M_2 constituent is likely due to a transfer of energy from other constituents.

Table V-2 presents the phase delay of the M_2 tide at all tide gage locations compared to the offshore gage at Cockle Cove Beach. Phase delay is another indication of tidal damping, and results with a later high tide at inland locations. The greater the frictional effects, the longer the delay between locations. The delays in Mill Pond and Little Mill Pond are nearly equal, as a result of their proximity to each other. More significant damping is seen in another area of Stage Harbor, at Oyster Pond, with a delay of 36.5 minutes, which is more than twice the delay of the Mill Ponds. This difference is primarily due to the flooding of tidal flats in the Oyster Pond River/Oyster Pond system, as well as the shallow constricted channel of Oyster Pond River. Similar to the behavior of the amplitude of M_2 tide, the largest delay of one hour occurs in Sulphur Springs (location C5) relative to offshore. Taylors Pond also exhibits a significant delay of almost a half hour.

Analysis of the data shows that the Oyster Pond, Sulphur Springs, and Taylors Pond systems, with shallow intertidal flats, expansive salt marsh regions, and winding channels and creeks, distorts the tide significantly relative to offshore Cockle Cove Beach, in Nantucket Sound. This distortion of the tide is evidenced as reduction in M_2 tide amplitude and M_2 phase delays.

Table V-2. M_2 Tidal Attenuation Stage Harbor and South Coast Embayments, Chatham, July-August 2000 (Delay in minutes relative to offshore of Cockle Cove Beach).

TDR Location	Delay (minutes)
Offshore	--
Little Mill Pond	12.89
Mill Pond	13.95
Taylors Pond	27.39
Oyster Pond	36.47
Sulphur Springs	59.22

For Oyster Pond and the South Coast Embayments flow restrictions modify the duration of the ebb and flood tide stages to a longer ebb duration (a slower, gradual draining of the estuary) and a briefer flood tide (Figure V-27). Nantucket Sound tides have a flood duration of approximately 7 hours, with an ebb duration of approximately 5 hours. The top plot of Figure V-27 demonstrates the modification to the tide signal in Oyster Pond relative to the remainder of the Stage Harbor complex and the offshore tide. In the lower two plots, the shorter duration of the flood tide in Sulphur Springs and Taylors Pond is more clearly seen with a flood duration of approximately 4 hours and an ebb of approximately 8 hours in duration.

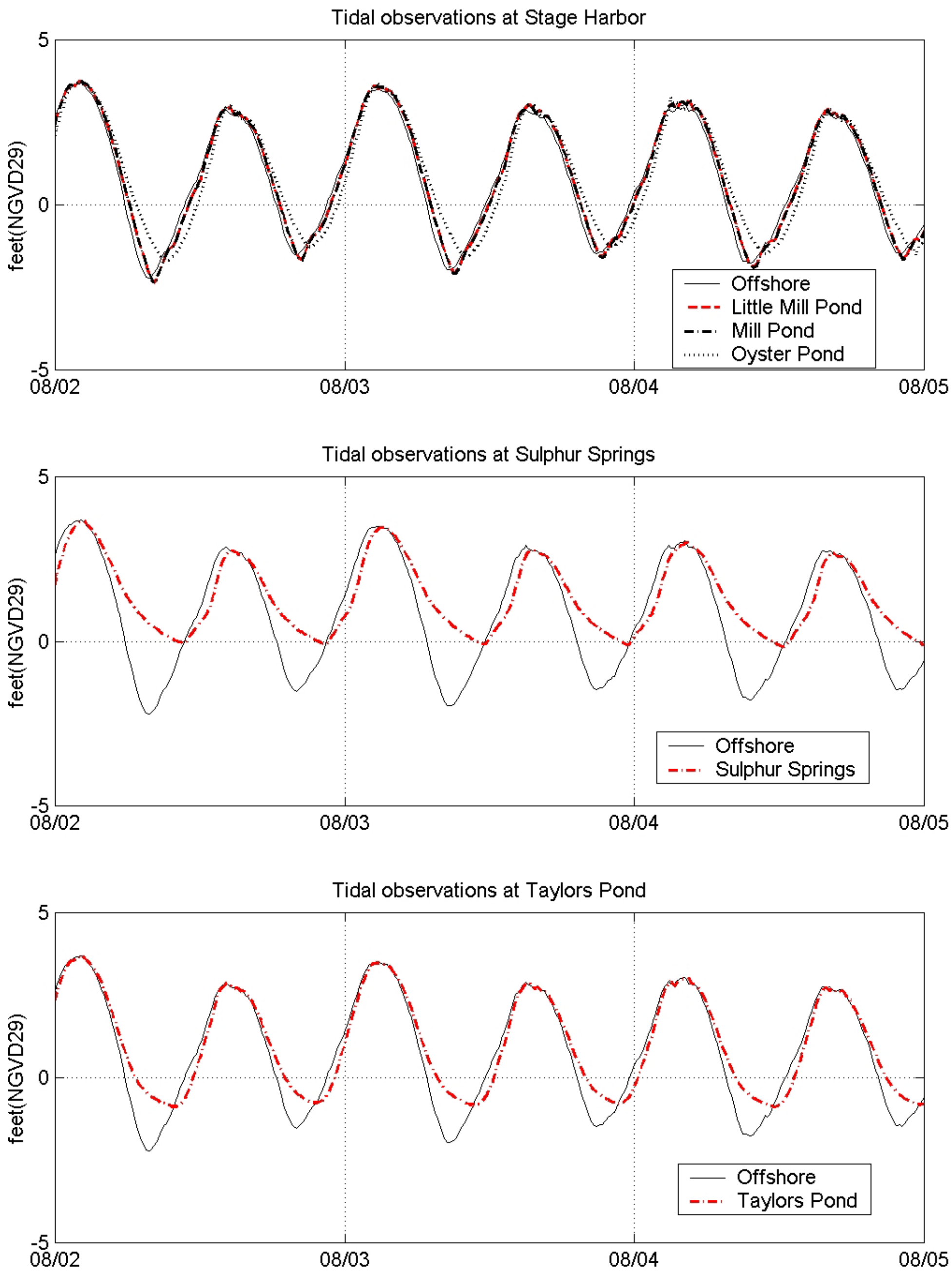

Figure V-27. Water elevation variations for a 3-day period in the Stage Harbor, Sulphur Springs, and Taylors Pond systems. Each plot depicts the Nantucket sound signal (offshore) overlaid with measurements obtained in the inland estuaries. Notice the reduced amplitude as well as the delay in times of high- and low- tide relative to offshore due to frictional damping through the systems.

For locations where the flood tide is shorter in duration than the ebb tide (e.g., Sulphur Springs), currents during the flood stage will be greater than during the ebb, since approximately the same amount of water volume must enter the system on the flood as leaves on the ebb. An example of this phenomenon is the Oyster Pond River inlet, where measured tidal currents were greater during the flood cycle than the ebb cycle. Estuarine systems of this type are referred to as 'flood-dominant'. Flood dominant systems tend to be sediment traps, where sediments transported into the system during flood tide often settle, causing long-term accretion or shoaling. The characteristics of the tidal signal can be utilized to indicate whether an estuarine system is likely to be a sediment trap for fine-grained materials, since trapping of organic sediments is often related to increased benthic flux during the summer months.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for Stage Harbor and the South Coast Embayments is presented in Table V-3, compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 23 known harmonic constituents). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary.

Table V-3. Percentages of Tidal versus Non-Tidal Energy, Stage Harbor and South Coast Embayments, July to August 2000

TDR Location	Total Variance ($ft^2 \cdot sec$)	Total(%)	Tidal (%)	Non-tidal (%)
Offshore	1.929	100%	98.9	1.1
Little Mill Pond	2.042	100%	98.6	1.4
Mill Pond	2.057	100%	98.7	1.3
Oyster Pond	1.909	100%	98.8	1.2
Sulphur Springs	0.874	100%	97.3	2.7
Taylors Pond	1.530	100%	98.7	1.3

Table V-3 shows that the percentage of tidal energy was largest in the offshore signal in Nantucket Sound; as should be expected given the tidal attenuation through the system. In general, the energy of the signal decreases with distance from the offshore gage, with the lowest energy found in upper regions of the ponds. The analysis also shows that tides are responsible for almost 99% of the water level changes in the Stage Harbor system and South Coast Embayments; wind effects in these data sets were negligible. In Sulphur Springs, tides are still responsible for over 97% of the elevation variation, with inputs from other sources accounting for the remaining energy. This relative increase in non-tidal energy within this system is likely due to the decrease in tidal energy as a result of frictional forces rather than a growth of residual forces.

V.3.2.1.2 Current Measurements

Current measurements in the Stage Harbor region, surveyed on August 16, 2000, provided observation of the temporal and spatial variability of the flow regime during a tidal cycle. The survey was designed to observe tidal flow through the Stage Harbor inlet, and how it was divided between the Oyster Pond River inlet, and the mouth of Mill Pond at hourly intervals. The current measurements observed during the flood and ebb tides at each constriction can be seen in FiguresV-28 throughV-33. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. For example, at the Stage Harbor inlet, positive along-channel is in the direction of northeast, and positive cross-channel is in the direction of southeast. In the lower left panel of the figures, the mean current or average currents across the channel are shown relative to the shoreline. The lower right panel indicates the stage of the tide during the transect illustrated (shown by a vertical line through the water elevation curve).

Tidal currents through the Stage Harbor inlet reached maximum speeds of approximately 3.3 ft/sec directed out of the estuary. During periods of maximum currents (flood and ebb) the inlet tidal flows were vertically coherent, with negligible stratification (FiguresV-28 andV-29) and ran parallel to the main navigation channel. During slack-water periods, there was an indication of mildly stratified flows, evidenced by an abrupt change in horizontal current direction in the water column. Maximum volume flux through the Stage Harbor inlet during flood tide was 5,750 ft^3/sec, while the maximum flux during ebb conditions was slightly more, -7,250 ft^3/sec. These flow measurements are consistent with the tide plots in Figure V-28, which show a longer duration flood stage relative to the duration of the ebb stage of the tide at Stage Harbor Inlet.

The channel through the Oyster Pond River inlet is along the north bank of the river, on average resulting in stronger currents along the northern side of the inlet reaching a maximum of approximately 2.0 ft/sec. During flood conditions, the currents are focused through the channel (Figure V-30), compared to ebb conditions where the flow is distributed relatively evenly across the inlet (Figure V-31). Volume flow rates reached a maximum of 2,310 ft^3/sec during flood conditions, and a maximum ebb flow rate of –1,790 ft^3/sec at the mouth of the Oyster Pond River. These flow measurements are consistent with the tide plots in Figure V-27, which show a longer duration ebb stage relative to the duration of the flood stage of the tide at Oyster Pond.

The third transect, measured south of the bridge at the mouth of Mill Pond showed the most variability in the along-channel tidal currents. The bridge begins approximately 210 feet along the transect (denoted by black line across top panel in Figure V-32), however the flow under the bridge is attenuated at the surface by wooden boards across the first two sets of pilings on the western side. As a result, the tidal currents are focused towards the center of the bridge through the largest opening, which is apparent during the ebb tide in Figure V-33, with a maximum current of approximately 2.0 ft/sec. At the mouth of Mill Pond, the maximum flood flow rate was 870 ft^3/sec, and the maximum ebb flow rate was –890 ft^3/sec. Again, these flow measurements are consistent with the tide plots in Figure V-27, which show a longer duration flood stage relative to the duration of the ebb stage of the tide at Mill Pond.

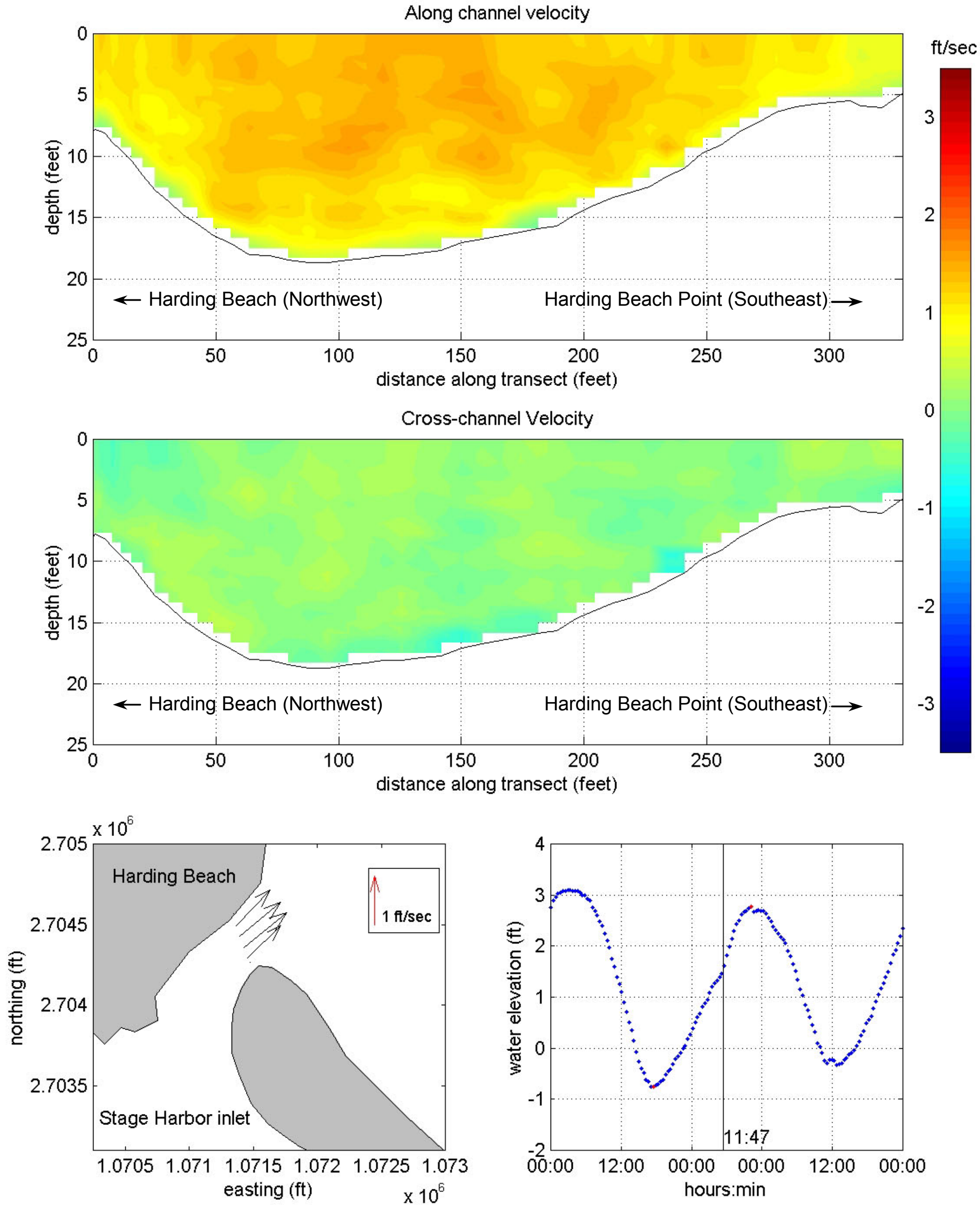

Figure V-28. Color contour plots of along-channel and cross-channel velocity components for transect line 1 run northwest-to-southeast across the Stage Harbor inlet measured at 11:47 on August 16, 2000 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

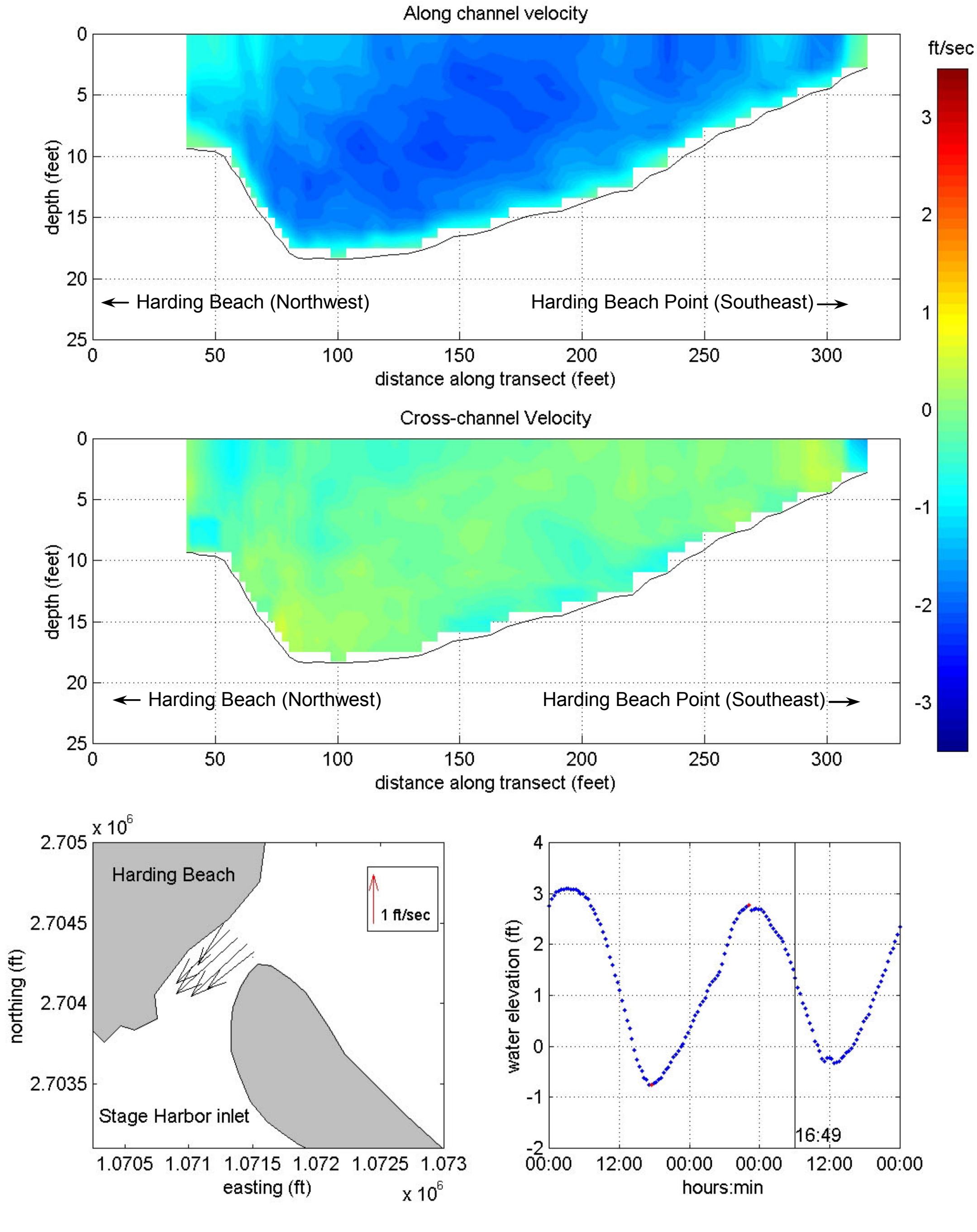

Figure V-29. Color contour plots of along-channel and cross-channel velocity components for transect line 1 run northwest-to-southeast across the Stage Harbor inlet measured at 16:49 on August 16, 2000 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

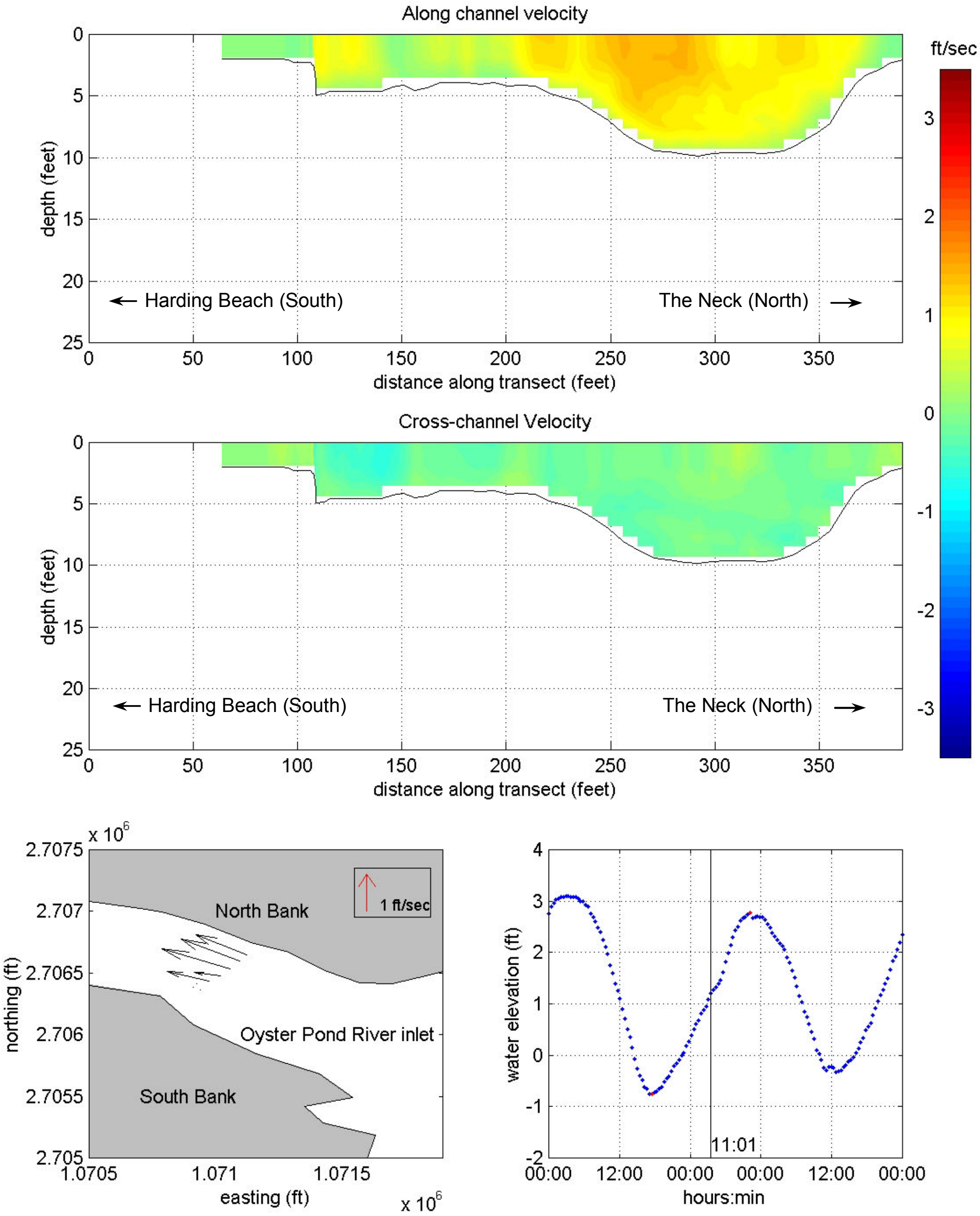

Figure V-30. Color contour plots of along-channel and cross-channel velocity components for transect line 2 run south-to-north across the Oyster Pond River inlet measured at 11:01 on August 16, 2000 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

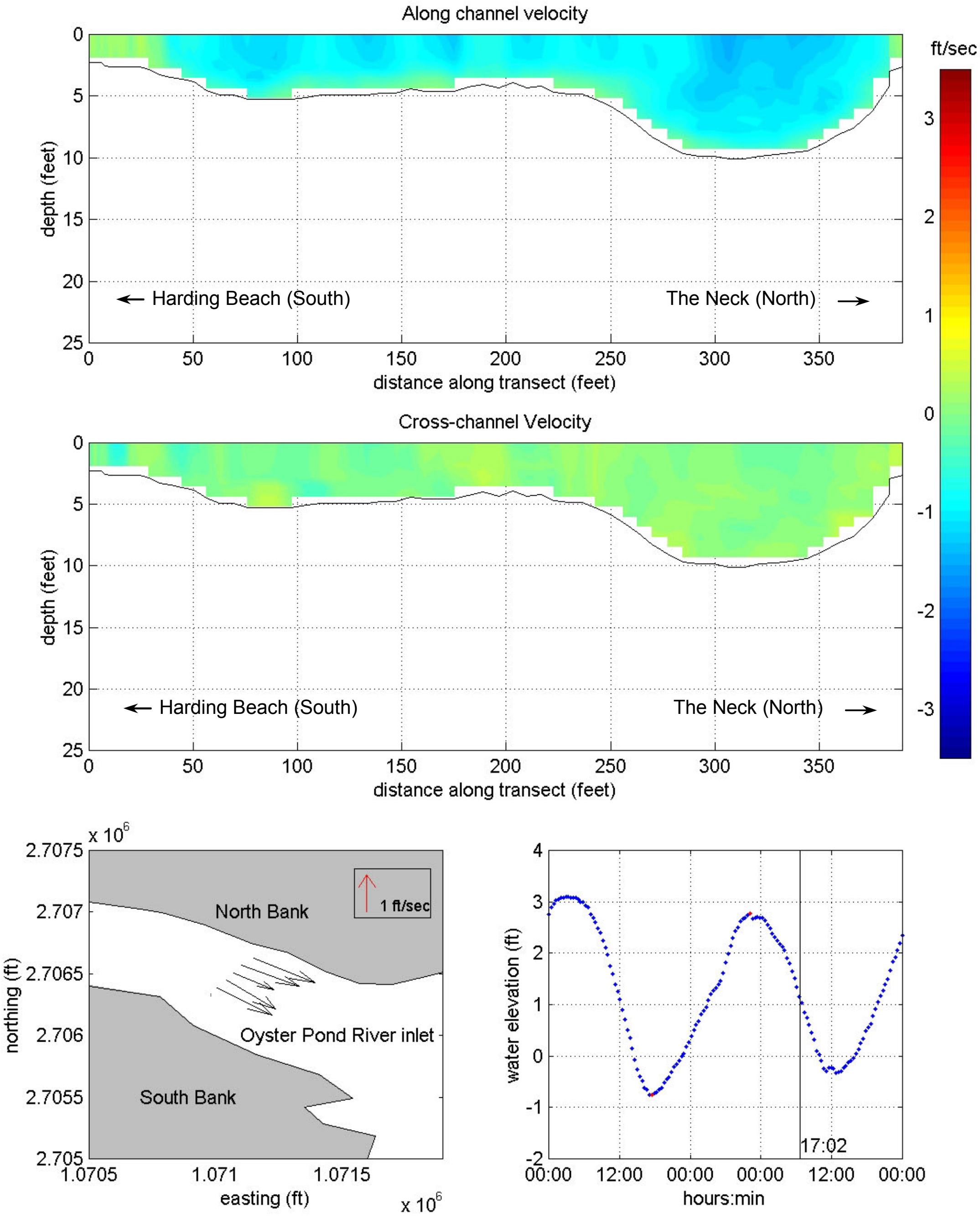

Figure V-31. Color contour plots of along-channel and cross-channel velocity components for transect line 2 run south-to-north across the Oyster Pond River inlet measured at 17:02 on August 16, 2000 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

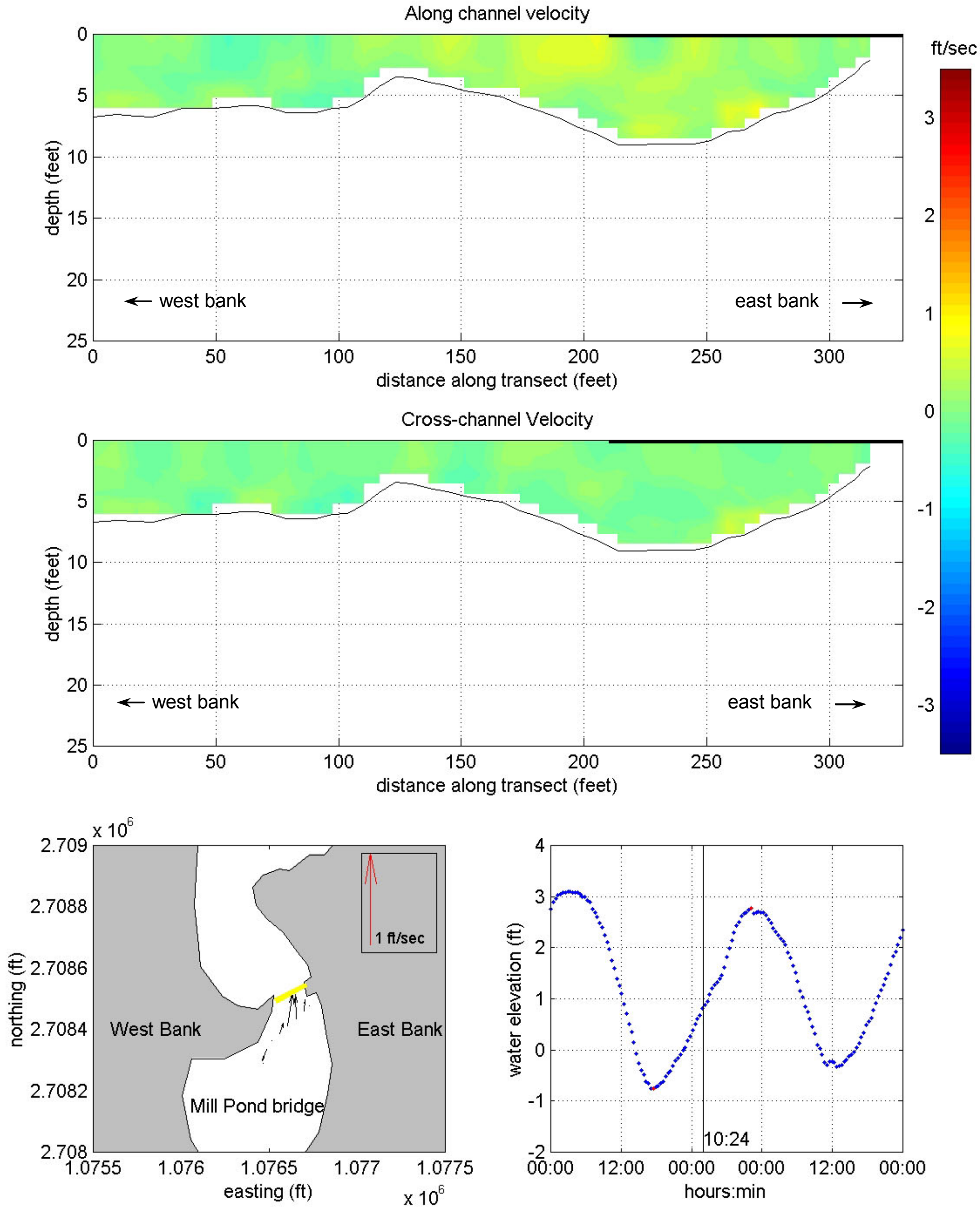

Figure V-32. Color contour plots of along-channel and cross-channel velocity components for transect line 3 run southwest-to-northeast across the south side of Mill Pond bridge measured at 10:24 on August 16, 2000 during the flood tide. The location of the bridge is indicated by a heavy black line at 0 ft depth from 210 to 350 feet along the transect in the top and middle panels, and a yellow line in the lower left panel.

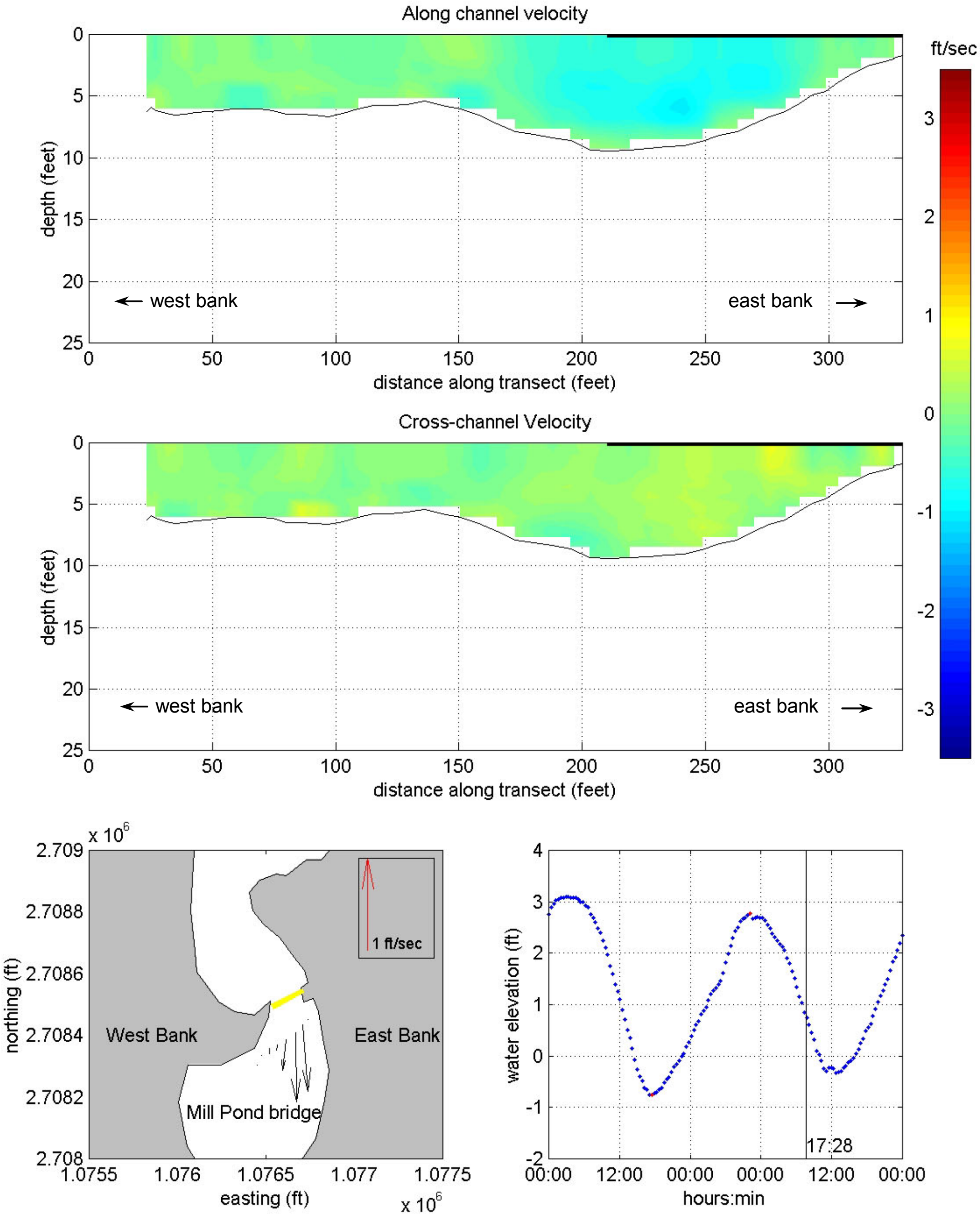

Figure V-33. Color contour plots of along-channel and cross-channel velocity components for transect line 3 run southwest-to-northeast across the south side of Mill Pond bridge measured at 17:28 on August 16, 2000 during the ebb tide. The location of the bridge is indicated by a heavy black line at 0 ft depth from 210 to 350 feet along the transect in the top and middle panels, and a yellow line in the lower left panel.

V.3.2.2 Pleasant Bay Region

V.3.2.2.1 Tidal Harmonic Analysis

Figure V-18 shows tidal elevations for the period August 22 through September 27, 2000 at five locations: Chatham Yacht Club (location P1 in Figure V-15), Crows Pond (location P2), Ryder Cove (location P3), Frost Fish Creek (location P4), and Muddy Creek (location P5). The curves have a predominant 12.42-hour variation around the lunar semi-diurnal (twice-a-day), or M_2, tidal constituent. The maximum (spring) tide range occurred on August 28 with a magnitude of approximately 5.5 feet, and the minimum (neap) tide range of approximately 2.6 feet occurred on September 8. Muddy Creek and Frost Fish Creek are long, narrow estuaries that are constricted at their entrances to the larger estuaries by culverts. The flow control features (i.e., culverts and weirs) of these two systems substantially attenuate the tidal signal.

The amplitudes of the eight largest tidal constituents from the tidal harmonic analysis are presented in Table V-4. The strongest contributor to the signal is the M_2 tide with an amplitude of 1.81 feet in Pleasant Bay (Chatham Yacht Club) and a range (twice the amplitude) of 3.62 feet. The diurnal tides, K_1 and O_1, possess amplitudes of approximately 0.25 feet. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, contribute with amplitudes of 0.23 feet and 0.36 feet, respectively.

Table V-5 presents the phase delay of the M_2 tide at all of the tide gage locations in the Pleasant Bay region compared to the Chatham Yacht Club gage. This comparison reinforces the lack of attenuation in Bassing Harbor, Ryder Cove and Crows Pond relative to Pleasant Bay. The flow restriction by culverts in Frost Fish Creek and Muddy Creek result in significant phase delays of the M_2 tide of over 2 hours in both systems. Muddy creek and the upper reaches of Frost Fish Creek drain to the larger estuaries through culverts, which inhibits the tidal flow, resulting in damping of the tidal signal.

Although the Chatham Yacht Club gage originally was intended as the forcing tide for both the Bassing Harbor and Muddy Creek systems, the tide phase at the Yacht Club indicated that it would be inappropriate to act as the model forcing for the Bassing Harbor system. Instead, the Ryder Cove data was utilized as the forcing data for Bassing Harbor. A more complete description of this approach is discussed in the modeling section.

Table V-4. Tidal constituents for Bassing Harbor/Muddy Creek, Chatham, August-September 2000

	Amplitude (feet)							
Constituent	M2	M4	M6	S2	N2	K1	O1	Msf
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Chatham Yacht Club	1.811	0.277	0.035	0.231	0.362	0.248	0.273	0.244
Ryder Cove	1.862	0.203	0.060	0.242	0.374	0.245	0.275	0.245
Crows Pond	1.860	0.228	0.049	0.243	0.377	0.250	0.275	0.256
Frost Fish Creek	0.161	0.036	0.004	0.027	0.041	0.052	0.064	0.114
Muddy Creek	0.296	0.051	0.003	0.037	0.055	0.077	0.088	0.205

Table V-5. M$_2$ Tidal Attenuation Bassing Harbor/Muddy Creek systems August-September 2000 (Delay in minutes relative to Chatham Yacht Club)	
TDR location	Delay (minutes)
Ryder Cove	-15.95
Crows Pond	-12.12
Chatham Yacht Club	--
Frost Fish Creek	122.13
Muddy Creek	141.81

Table V-6 shows the relative energy of tidal versus non-tidal processes at the tide gage locations in the Pleasant Bay region. The signal variance (or energy) of each time series was computed to calculate the percentages. Tides are responsible for approximately 97% of the water level changes at Chatham Yacht Club, Ryder Cove, and Crows Pond; wind effects in the data for these three estuaries were negligible. In the creeks, tides are only responsible for approximately 70% of the elevation variation, with inputs from other sources accounting for the remaining energy. This relative increase in non-tidal energy within the creeks is likely due to the decrease in tidal energy as a result of attenuation of the flow through the constrictions rather than a growth of residual forces. Variations in the water surface elevation of the creeks are also affected by freshwater discharge into the systems.

Table V-6. Percentages of tidal versus non-tidal energy Bassing Harbor/Muddy Creek August-September 2000.				
TDR location	Total Variance ($ft^2 \cdot sec$)	Total(%)	Tidal (%)	Non-tidal (%)
Chatham Yacht Club	1.998	100%	97.0	3.0
Ryder Cove	2.082	100%	97.1	2.9
Crows Pond	2.092	100%	97.0	3.0
Frost Fish Creek	0.037	100%	70.7	29.3
Muddy Creek	0.105	100%	73.9	26.1

V.3.2.2.2 Current Measurements

Cross-channel current measurements were surveyed through a tidal cycle in the Bassing Harbor system on September 1, 2000 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow through Bassing Harbor inlet, and the division of flow between Crows Pond and Ryder Cove/Frost Fish Creek at hourly intervals. FiguresV-34 throughV-39 show color contours of current measurements observed during the flood and ebb tides at each of the three transects. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. For example, at the Bassing Harbor inlet, positive along-channel flow is westerly, and positive cross-channel flow is moving north. In the lower left panel of the figures, the mean current or average currents across the channel are shown relative to the shoreline. The lower right panel indicates the stage of the tide that the survey was taken by a vertical line through the water elevation curve.

The complex geometry of Bassing Harbor inlet results in an unequal distribution of currents across the entrance. During flood tide, maximum currents were focused through the primary channel in a west-southwest direction (Figure V-34), with additional flow across the southern portion of the inlet. The curvature of the shoreline of Bassing Harbor and the presence of Fox Hill appears to modify the flow out of the harbor on the ebb tide. In Figure V-35 (lower left panel), ebb currents are distributed more evenly across the inlet, and flow almost perpendicular to the direction of maximum flood currents. In a system with a linear channel, dominant flood and ebb currents flow along the same line, but in opposite directions (180°). In Bassing Harbor, the curvature of the channel with the shoreline complicates the rotation of currents into along-channel and cross-channel components. As a result of the rotation based on the assumption of a linear channel, the color contours in Figure V-35 (top and middle panel) show that a large portion of the tidal flow energy in contained in the cross-channel component during the ebb tide. Tidal currents through the Bassing Harbor inlet reached a maximum of approximately 3.2 ft/sec directed out of the harbor during ebb tide. The maximum volume flow rate through the Bassing Harbor inlet was 4,880 ft^3/sec during the flood tide, and the maximum ebb volume flow rate was –1,670 ft^3/sec.

The second transect was measured from east-to-west across the mouth of Ryder Cove, which also connects to Frost Fish Creek. The dominant flood tidal currents were focused through the channel at a maximum velocity of approximately 2.3 ft/sec (Figure V-36). The transect was begun to the south of a pier on the east side of the inlet, which may account for the presence of currents directed out of the estuary along the east bank. During the ebb tide, the current profiles were moderately stratified in the channel (Figure V-37), with stronger out-estuary velocities in the upper layers of the water column, and weaker in-estuary flow near the bottom of the channel. At the entrance to Ryder Cove/Frost Fish Creek, the volume flow rate reached a maximum during flood tide of 1,800 ft^3/sec, and a maximum of -990 ft^3/sec during the ebb tide.

The geometry of the shoreline at the mouth of Crows Pond shifts the cross channel position of the strongest currents from one side to the other during the flood-ebb tidal cycle. At the wide entrance to Crows Pond, the strongest flood currents into the estuary occur on the north side (Figure V-38), and the strongest ebb currents out of the estuary occur on the south side of the channel (Figure V-39). Maximum along-channel velocities were observed during the ebb tide at magnitudes of 3.2 ft/sec, but strong cross-channel components of ebb tidal currents are also seen as a result of rotation of currents relative to a linear channel. Volume flow rates reach a maximum of 1,600 ft^3/sec during the flood tide, and a maximum of -1,240 ft^3/sec during the ebb tide at the entrance to Crows Pond.

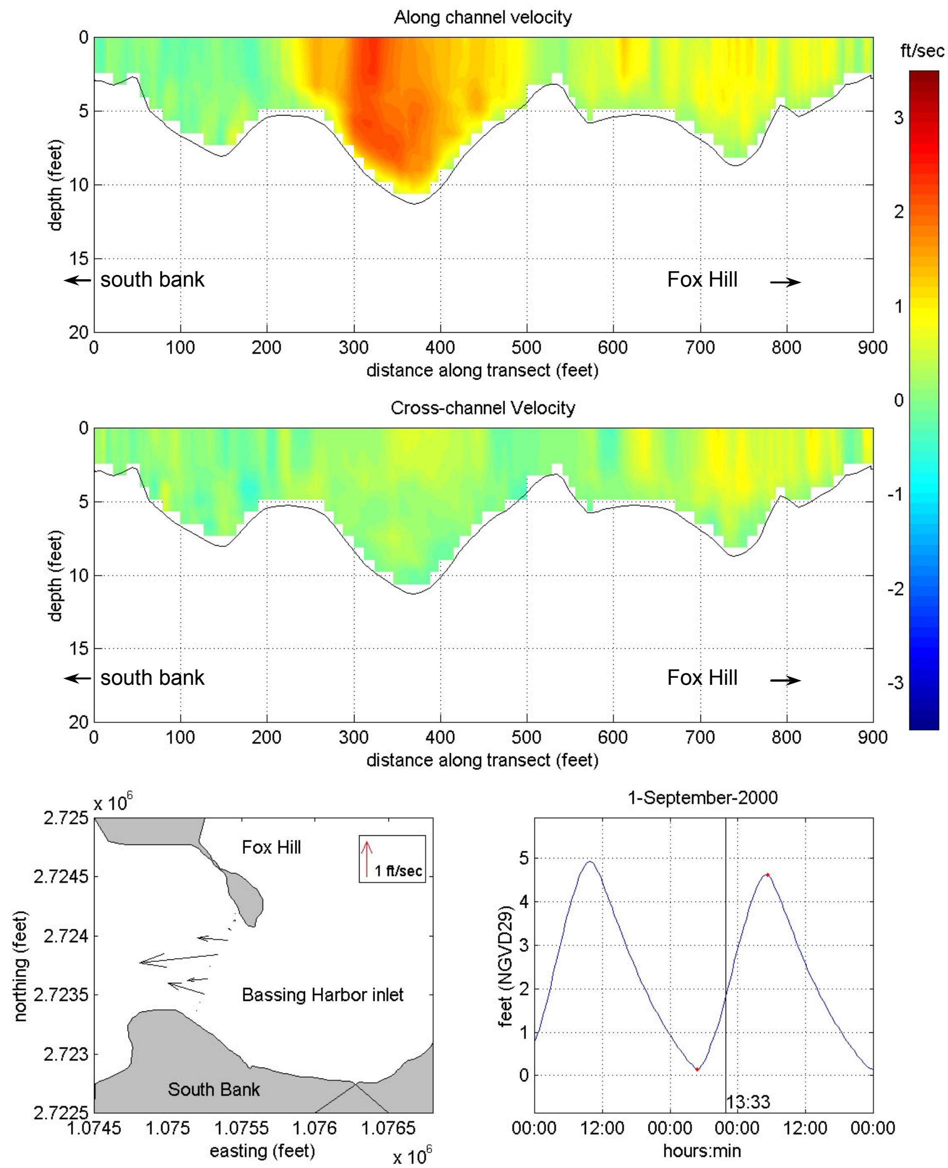

Figure V-34. Color contour plots of along-channel and cross-channel velocity components for transect line run south-to-north across the Bassing Harbor inlet measured at 13:33 on September 1, 2000 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

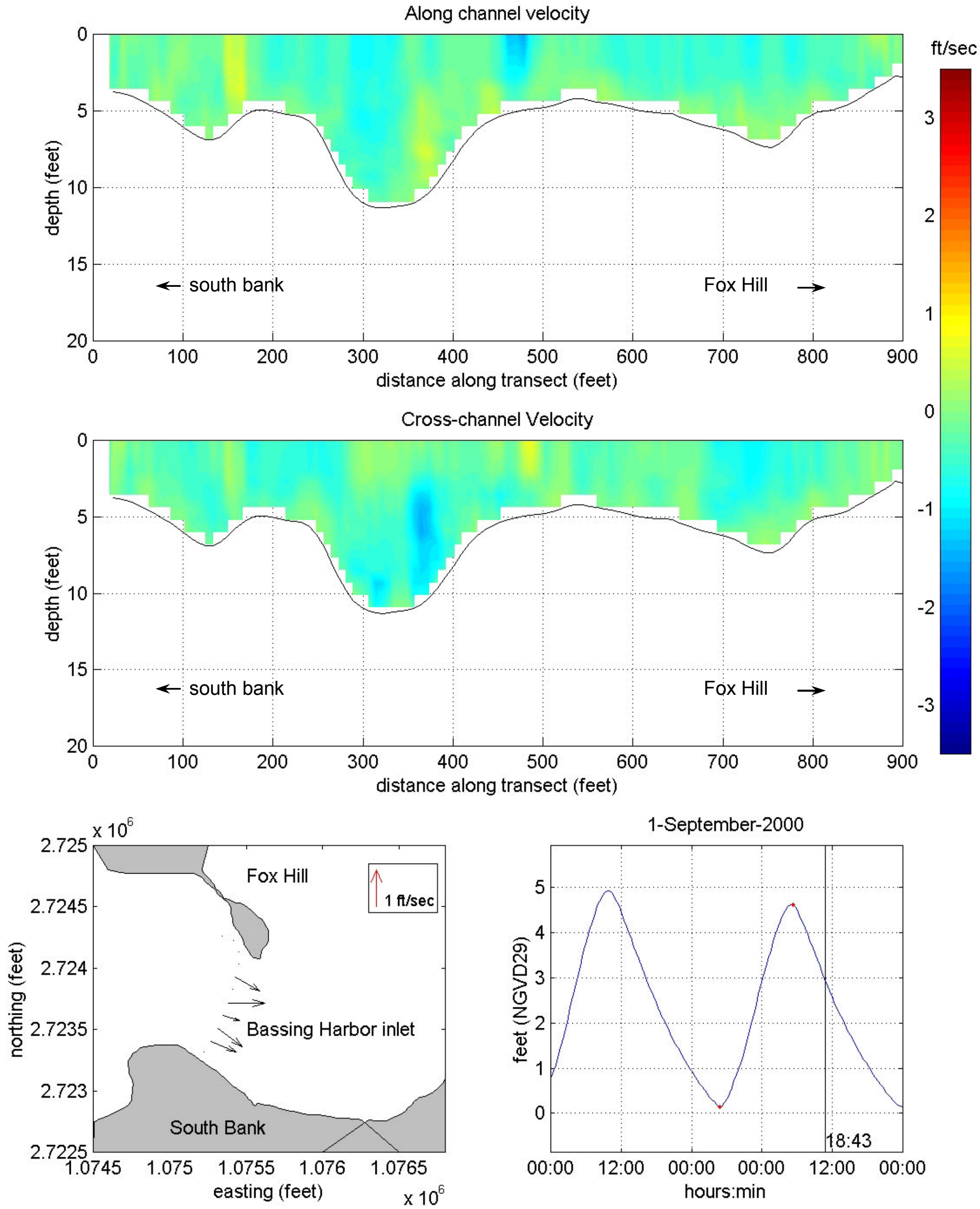

Figure V-35. Color contour plots of along-channel and cross-channel velocity components for transect line run south-to-north across the Bassing Harbor inlet measured at 18:43 on September 1, 2000 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

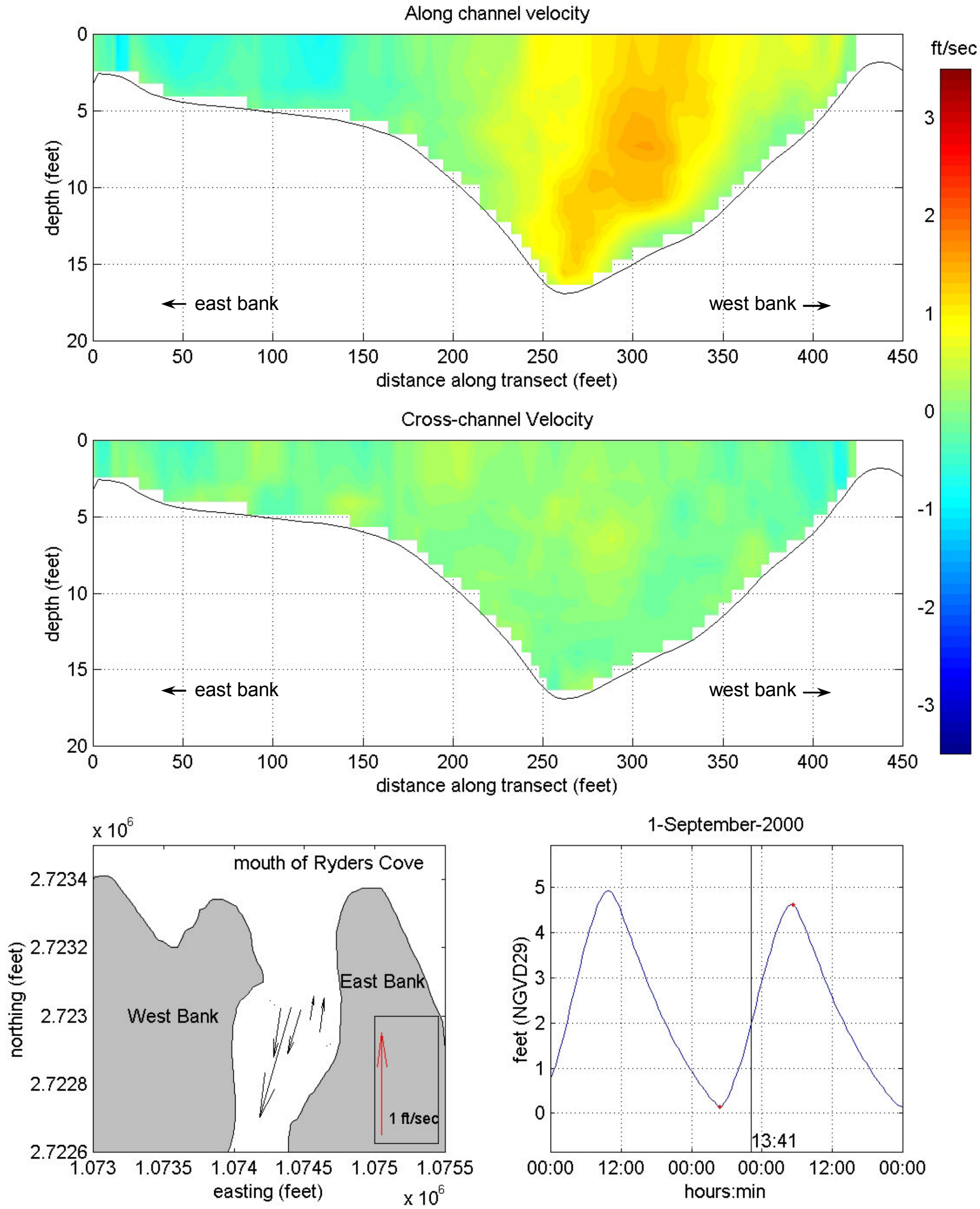

Figure V-36. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the mouth of Ryder Cove measured at 13:41 on September 1, 2000 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

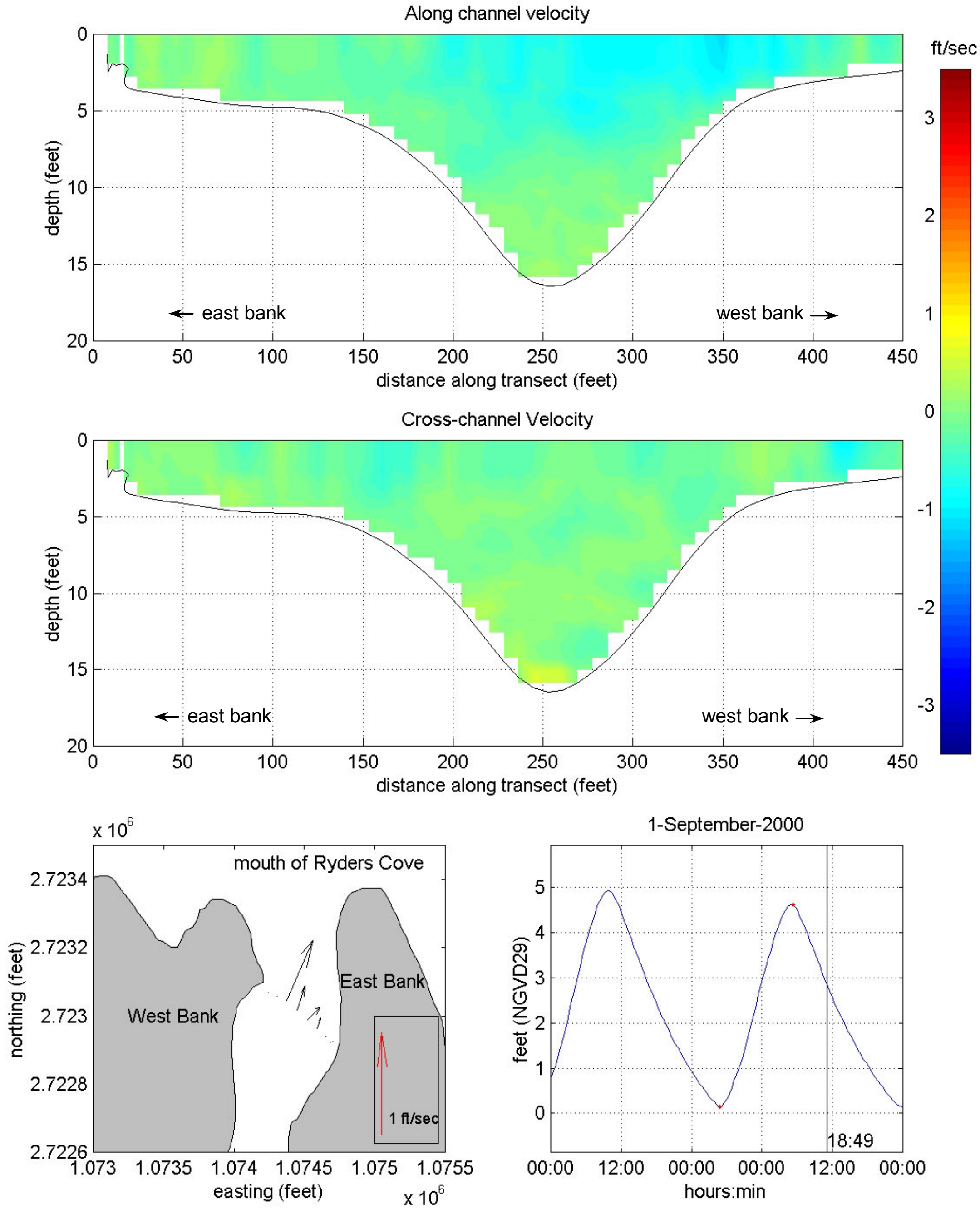

Figure V-37. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the mouth of Ryder Cove measured at 18:49 on September 1, 2000 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

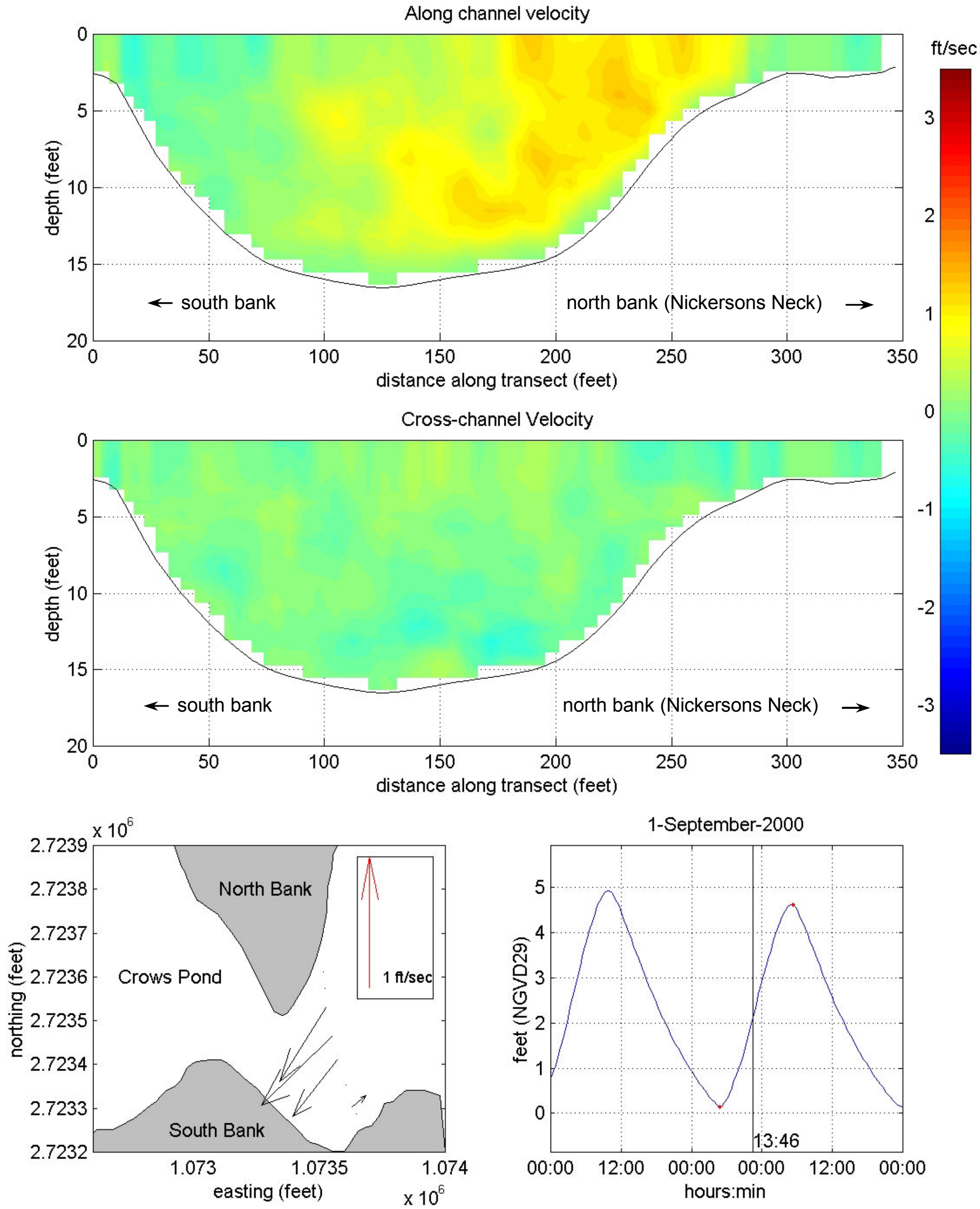

Figure V-38. Color contour plots of along-channel and cross-channel velocity components for transect line run south-to-north across the mouth of Crows Pond measured at 13:46 on September 1, 2000 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

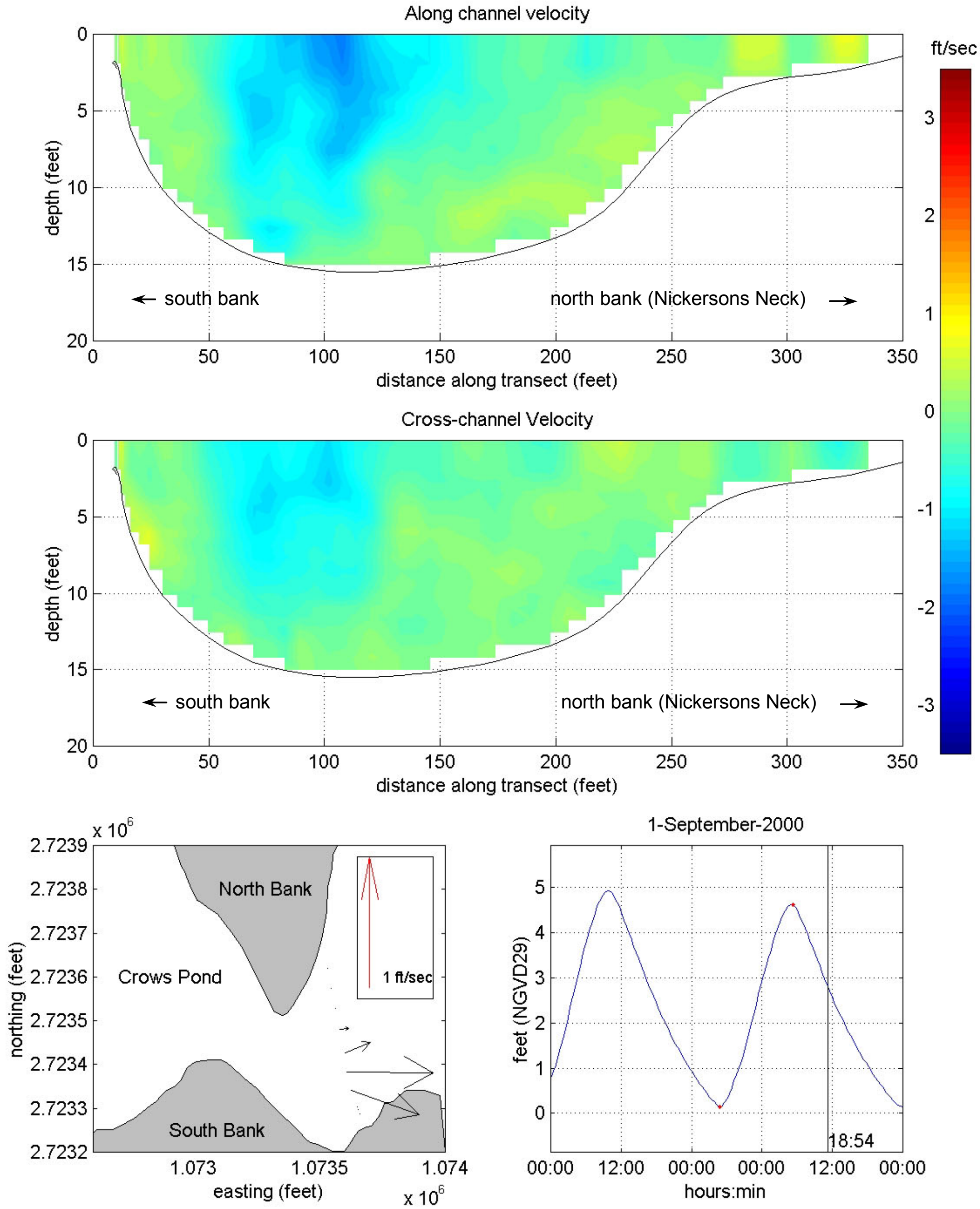

Figure V-39. Color contour plots of along-channel and cross-channel velocity components for transect line run south-to-north across the mouth of Crows Pond measured at 18:54 on September 1, 2000 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

V.4 HYDRODYNAMIC MODELING

This study focuses on five individual estuarine systems in Chatham, Massachusetts: Stage Harbor, Bassing Harbor, Sulphur Springs, Taylors Pond, and Muddy Creek. Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in these systems. The particular model employed was the RMA-2V model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2V for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Pleasant Bay, Falmouth "finger" Ponds, and Barnstable Harbor.

V.4.1 Model Theory

In its original form, RMA-2V was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by a Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2V is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the prototype system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore, unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.4.2 Model Setup

There are three main steps required to implement RMA-2V:

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using contour data developed for the Town's Geographic Information System (GIS), as well as 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of each system based on the tide gauge data collected in Nantucket Sound and Pleasant Bay. Freshwater recharge boundary conditions for Muddy Creek and Frost Fish Creek were specified to approximate average fresh water inputs to the systems. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several (15+) model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.4.2.1 Grid generation

The grid generation process was simplified by the use of the SMS package. The digitized shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary. Information about each grid is provided in Table V-7. Figures V-40 through V-44 illustrate the finite element grids for each system modeled: Stage Harbor, Bassing Harbor, Sulphur Springs, Taylors Pond, and Muddy Creek. With the exception of groundwater inputs entering Muddy Creek and Frost Fish Creek, the embayments were represented by two-dimensional (depth-averaged) elements.

The finite element grid for each system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of each estuary. Fine resolution was required to simulate the numerous channel constrictions that significantly impact the estuarine hydrodynamics. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Reference water depths at each node of the model were interpreted from bathymetry data obtained from a combination of sources, including 1) recent fathometer and/or ADCP surveys in Stage Harbor, Bassing Harbor, and Taylors Pond; 2) recent manual surveys of Muddy Creek, Upper Frost Fish Creek and Cockle Cove Creek; 3) existing NOAA data for Stage Harbor; 4) previous bathymetric survey of Bassing Harbor (ACI, 1997); and previous bathymetric surveys of the Sulphur Springs/Bucks Creek and Taylors Pond Systems (Stearns and Wheler, 1999)

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in marsh creeks and channels was designed to provide a more detailed analysis in these regions of rapidly varying flow. Also, elements through deep channels (e.g., Stage Harbor Inlet channel) were designed to account for rapid changes in bathymetry caused by inlet shoaling and scour processes. Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as Crows Pond, or Sulphur Springs. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

Areas of marsh in the South Coastal Embayments (i.e., Sulphur Springs/Bucks Creek, Cockle Cove Creek, and Taylors Pond/ Mill Creek) were included in the models because these marsh areas are a large portion of the total area of these systems, and have a significant effect on the hydrodynamics of these embayments. In the other modeled systems, marsh areas were not included in order to simplify the modeling effort without impacting model accuracy. This is justified by the fact that the models calibrated and verified well without the inclusion of areas of marsh.

Table V-7. Characteristics of numerical grids developed for hydrodynamic analyses.					
System	Nodes	Elements	Max. Depth (ft, NGVD)	Min. Depth (ft, NGVD)	location of max. depth
Stage Harbor	3973	1466	-18.4	0.0	Stage Harbor Inlet
Bassing Harbor	4419	1443	-18.3	2.3	Crows Pond
Sulphur Springs	7882	2728	-4.5	2.0	Bucks Creek
Taylors Pond	5202	1853	-11.4	2.0	Taylors Pond
Muddy Creek	2872	874	-4.1	0.7	Lower Muddy Creek

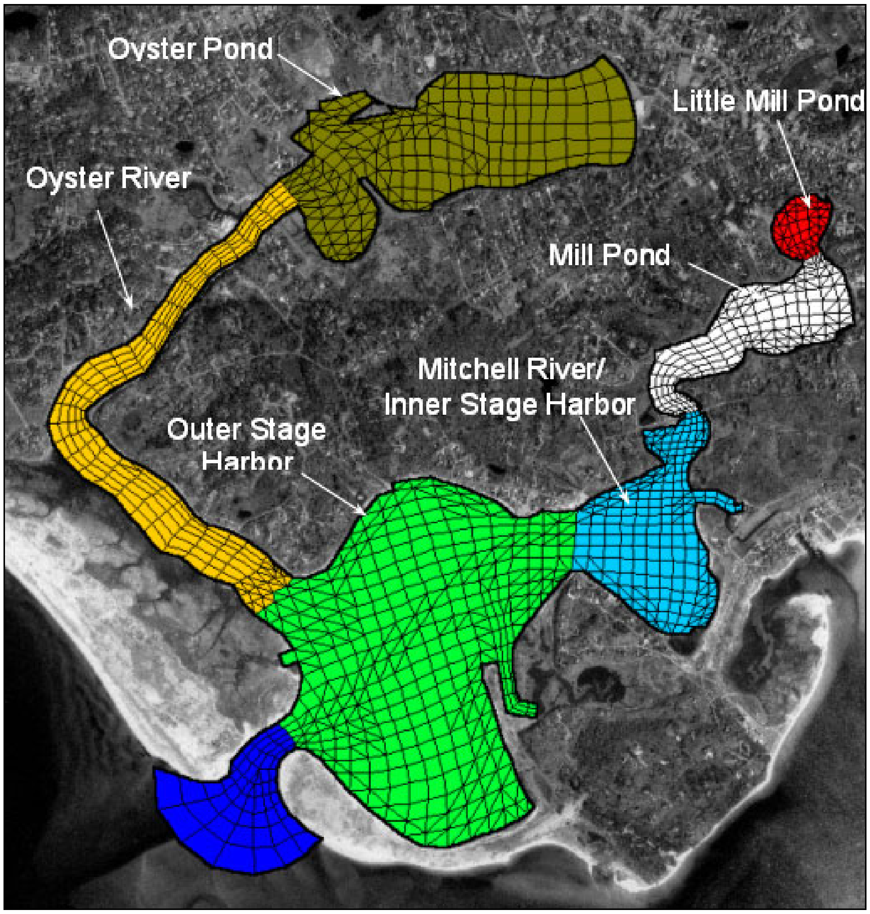

Figure V-40. Plot of numerical grid used for hydrodynamic modeling of Stage Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

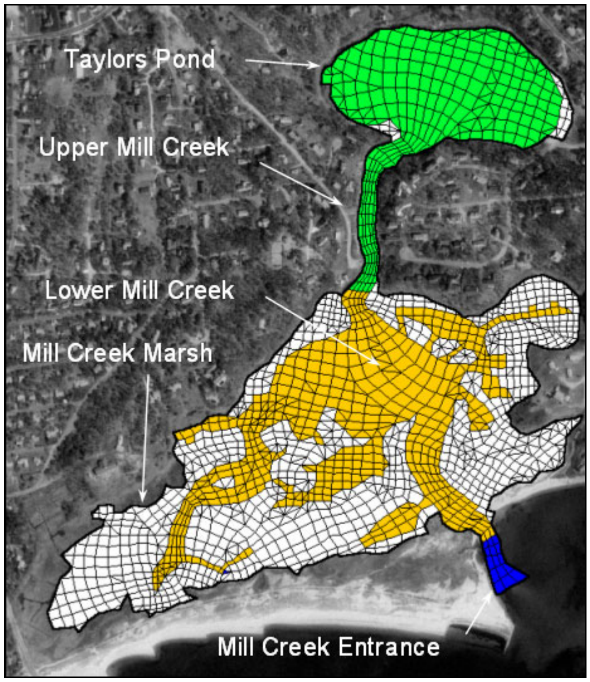

Figure V-41. Plot of numerical grid used for hydrodynamic modeling of Taylors Pond/Mill Creek system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

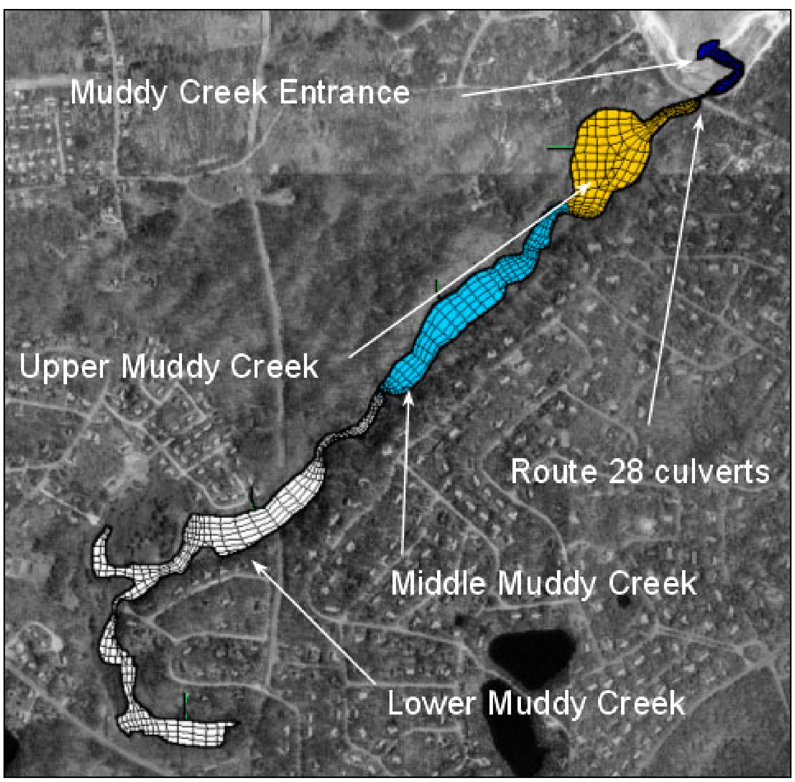

Figure V-42. Plot of numerical grid used for hydrodynamic modeling of Muddy Creek system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for the system.

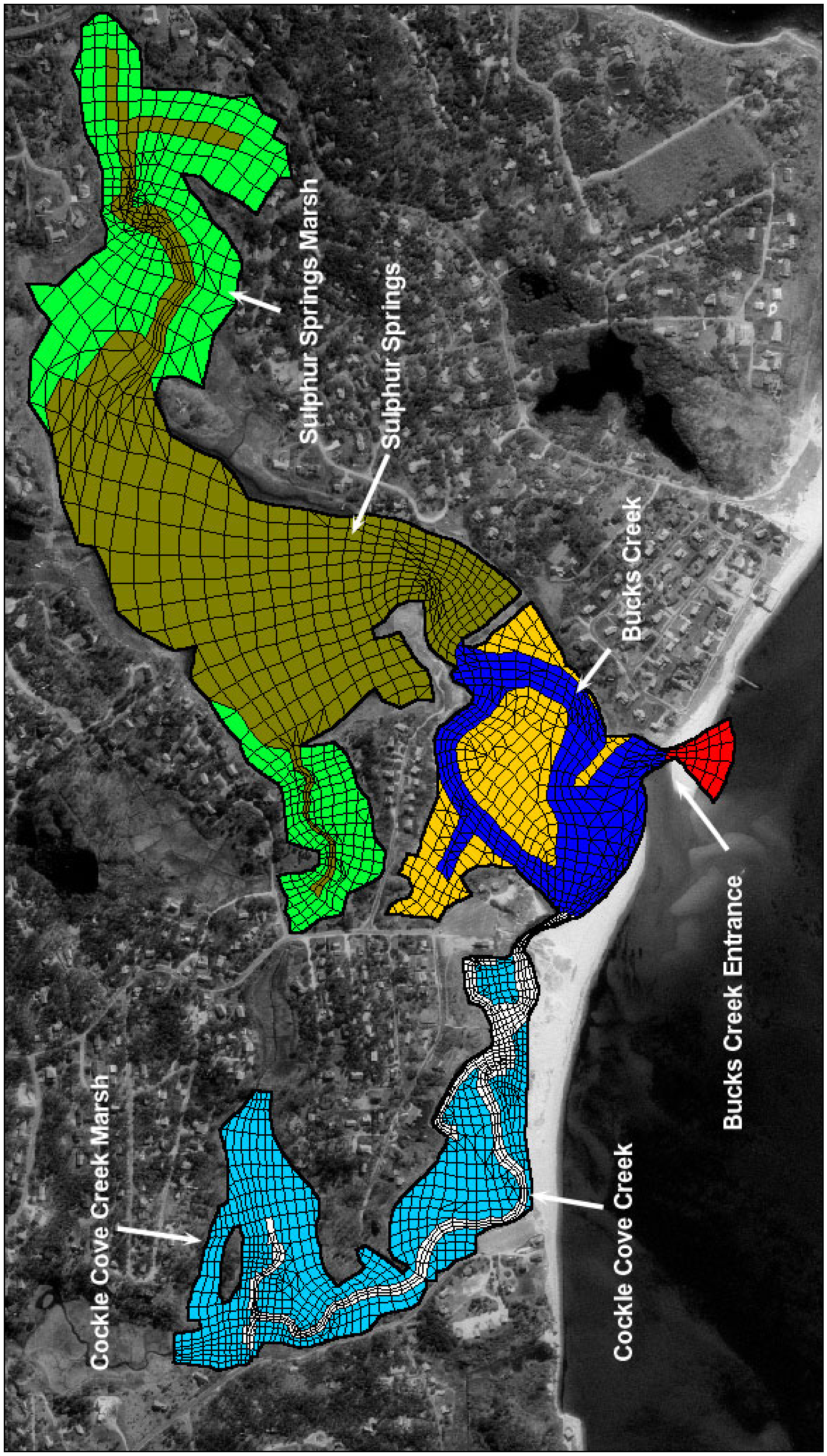

Figure V-43. Rotated view of numerical grid used for hydrodynamic modeling of Stage Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

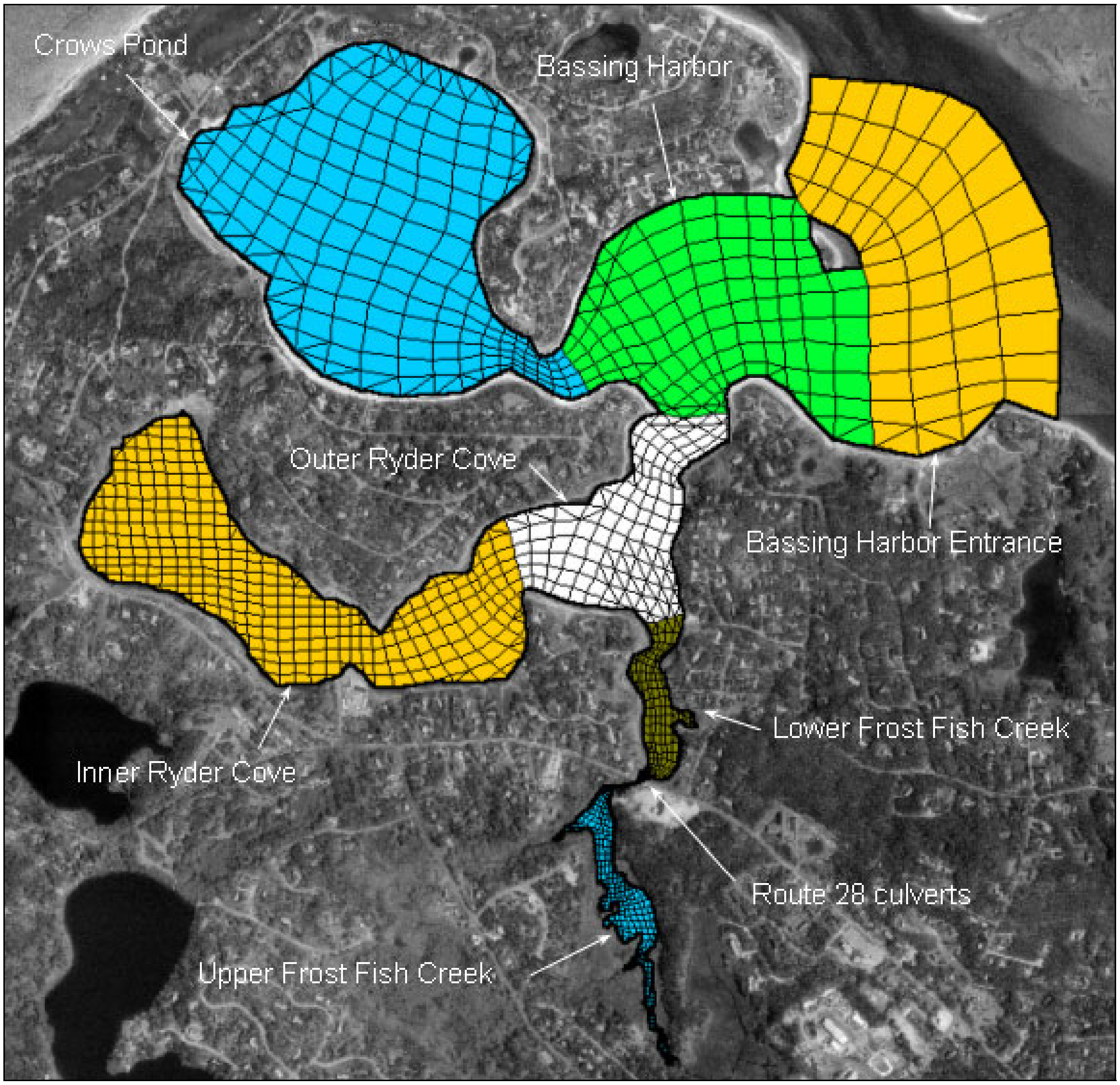

Figure V-44. Plot of numerical grid used for hydrodynamic modeling of Bassing Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

V.4.2.2 Boundary condition specification

Three types of boundary conditions were employed for the RMA-2V model: 1) "slip" boundaries, 2) freshwater inflow, and 3) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. Based on watershed areas and average rainfall, freshwater recharge (surface and ground water flows) was specified for Muddy Creek and Frost Fish Creek. The flow rates used in the model are 1.56 ft3/sec for Frost Fish Creek and 3.43 ft3/sec for Muddy Creek, based on an average rainfall of 16 inch/year (Cape Cod Commission, 1998) and watershed areas determined using the Town GIS (849 acres for Frost Fish Creek and 1863 acres for Muddy Creek). A tidal boundary condition was specified seaward of the inlet to each system. TDR measurements provided the required data. The rise and fall of the tide in Nantucket Sound and

Pleasant Bay is the primary driving force for estuarine circulation. Dynamic (time-varying) model simulations specified a new water surface elevation in Nantucket Sound (for Stage Harbor, Sulphur Springs, and Taylors Pond), and Pleasant Bay (for Bassing Harbor and Muddy Creek) every model time step minutes (12 minutes).

V.4.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for each system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Calibrated models provide a diagnostic tool to evaluate other scenarios (e.g., the effects of increasing the size of the Frost Fish Creek culverts to improve flushing). Numerous model simulations were required (typically 15+) for each estuary, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the flushing model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, a two-day period was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, a seven-day period was modeled to calibrate the model based on dominant tidal constituents discussed in Section III. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions.

The calibration was performed for a seven-day period beginning August 25, 2000 at 1800 EDT for the Pleasant Bay systems (i.e., Bassing Harbor and Muddy Creek), and beginning July 25, 2000 at 1600 EDT for the systems on Nantucket Sound (i.e., Stage Harbor, Sulphur Springs, and Taylors Pond). These representative time periods include the spring tide range of conditions, when the tide range largest, and resulting tidal currents are greater as well. To provide average tidal forcing conditions for the flushing analyses, a separate time period was chosen that spanned the transition between spring and neap tide ranges (bi-weekly maximum and minimum tidal ranges, respectively). For the flushing analysis the 7.25 day period (14 tide cycles) beginning July 31 2000, at 1300 EDT was used for the systems on Nantucket Sound, and a similar period beginning August 31 2000 at 0300 EDT was selected for the systems on Pleasant Bay.

The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.4.2.3.1 Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2V as a Manning coefficient. Initially, Manning's friction coefficients between 0.02 and 0.07 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for the smooth sandy channels in the entrance channel of each Pond, versus the silty bottom of the shallow regions in the upper portions of each Pond, which provided greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-8.

V.4.2.3.2 Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 50 and 100 lb-sec/ft2. Higher values (up to 300 lb-sec/ft2) were used on the marsh plain and in culverts.

V.4.2.3.3 Wetting and Drying/marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain as well as in intertidal regions in each of the systems. In the case of the marsh plains that are a part of the Sulphur Springs/Cockle Cove Creek and Mill Creek systems, wet/dry areas will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2V model which permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RM-2V to change the ability of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2V is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system, such as Sulphur Springs and Mill Creek.

Table V-8. Manning's Roughness coefficients used in simulations of modeled embayments.		
System	Embayment	Bottom Friction
Stage Harbor	Stage Harbor Entrance	0.030
	Lower Stage Harbor	0.030
	Mitchell River / Upper Stage Harbor	0.030
	Mill Pond	0.025
	Little Mill Pond	0.025
	Oyster Pond River	0.030
	Oyster Pond	0.030
Sulphur Springs	Bucks Creek Entrance	0.030
	Bucks Creek	0.030
	Sulphur Springs	0.030
	Sulphur Springs Marsh Plain	0.100
	Cockle Cove Creek	0.040
	Cockle Cove Creek Marsh Plain	0.070
Taylors Pond	Mill Creek Entrance	0.030
	Taylors Pond	0.025
	Mill Creek	0.027
	Mill Creek Marsh Plain	0.100
Bassing Harbor	Bassing Harbor Entrance	0.030
	Bassing Harbor	0.031
	Outer Ryder Cove	0.015
	Crows Pond	0.030
	Inner Ryder Cove	0.015
	Upper Frost Fish Creek	0.030
	Frost Fish Creek culverts	0.500
	Lower Frost Fish Creek	0.030
Muddy Creek	Muddy Creek Entrance	0.030
	Muddy Creek Culverts	0.150
	Muddy Creek	0.025

For Stage Harbor and Bassing Harbor, an alternate method was employed to simulate the periodic inundation and drying of tidal flats in these systems. Nodal wetting and drying is a feature of RMA-2V that allows grid elements to be removed and re-inserted during the course of the model run. Figure V-45 presents an example of how the computational grid is modified by element elimination. This figure shows the Stage Harbor model at a point just after low tide. White areas within the boundary of the mesh are elements that have gone dry, and as a result, have been removed temporarily from the model solution. The wetting and drying feature has two keys benefits for the simulation, 1) it enhances the stability of the model by eliminating nodes that have bottom elevations that are higher than the water surface elevation at that time, and 2) it reduces total model run time because node elimination can reduce the size of the computational grid significantly during periods of a model run. Wetting and drying is employed for estuarine systems with relatively shallow borders and/or tidal flats.

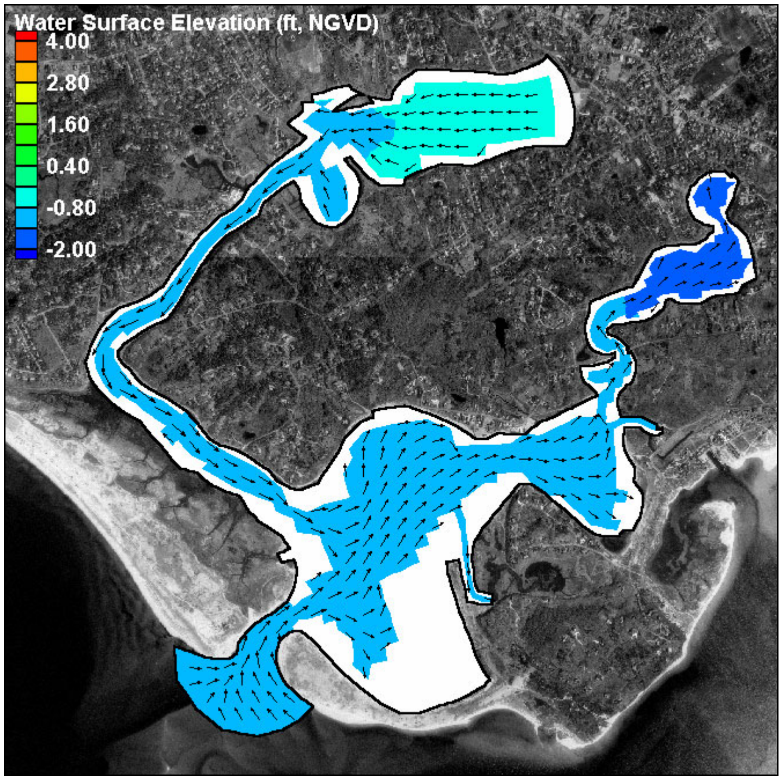

Figure V-45. Stage Harbor model at the inception of a flood tide, with white areas indicating dry elements.

V.4.2.3.4 Comparison of modeled tides and measured tide data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-46 through V-54 illustrate the seven-day calibration simulation along with a two-day sub-section. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Tables V-9 and V-4 for the calibration period differ from those in Table V-7 because constituents were computed for only the seven-day section of the thirty-days represented in Table V-7. Tables V-9 and V-10 compare tidal constituent height and time lag for modeled and measured tides at the TDR locations. Time lag represents the time required for a constituent to propagate from offshore (Nantucket Sound or Pleasant Bay) to each TDR location.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.1 ft, which was only slightly larger than the accuracy of the tide gages (0.032 ft). Generally, errors in modeled constituent amplitudes were of the order 0.01 ft. Time lag errors were typically less than the time increment resolved by the model (0.20 hours or 12 minutes), indicating good agreement between the model and data.

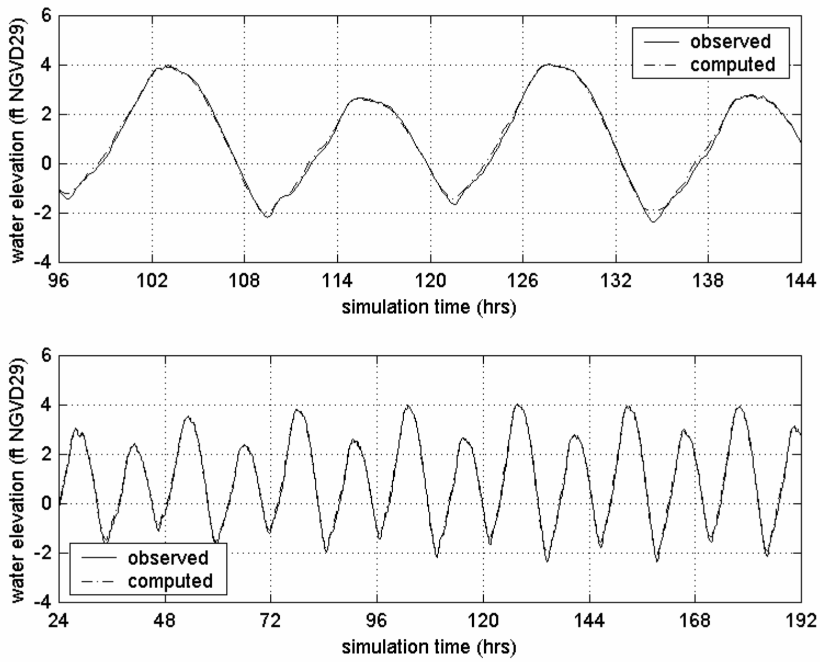

Figure V-46. Observed and computed water surface elevations during calibration time period, for Mill Pond.

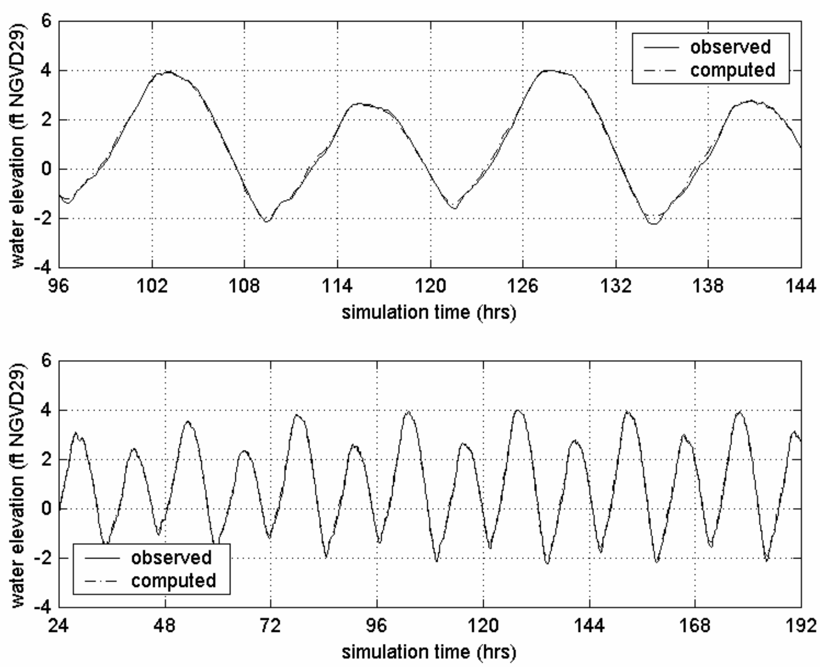

Figure V-47. Observed and computed water surface elevations during calibration time period, for Little Mill Pond.

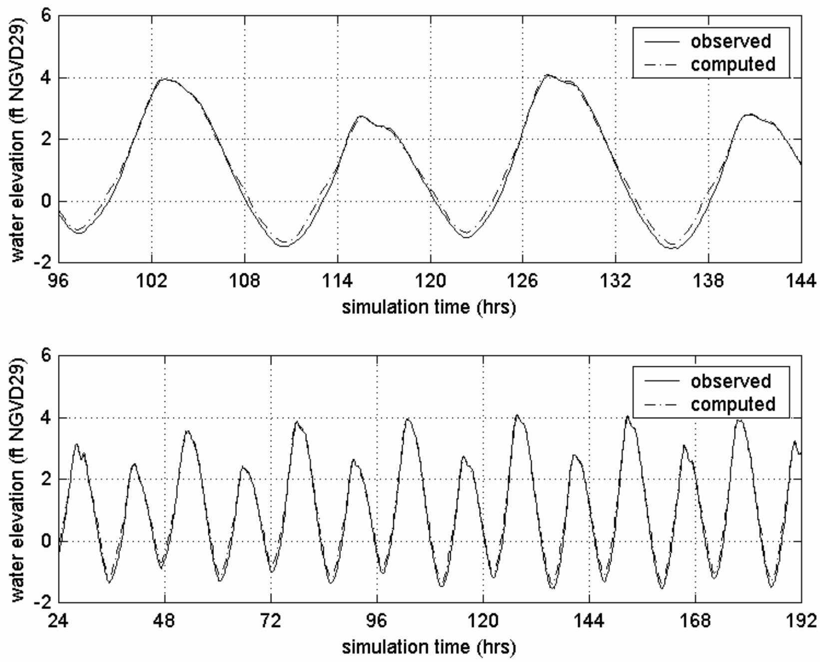

Figure V-48. Observed and computed water surface elevations during calibration time period, for Oyster Pond.

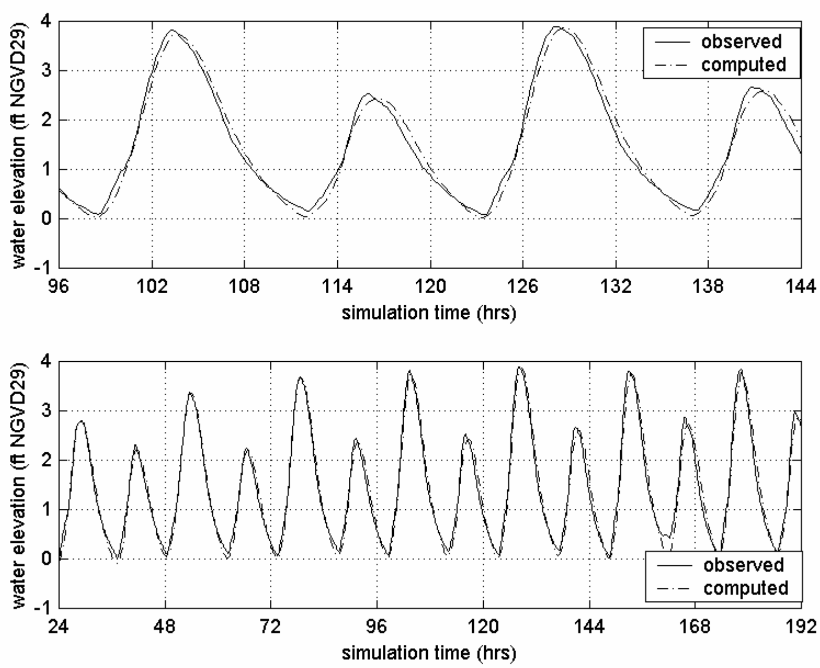

Figure V-49. Observed and computed water surface elevations during calibration time period, for Sulphur Springs.

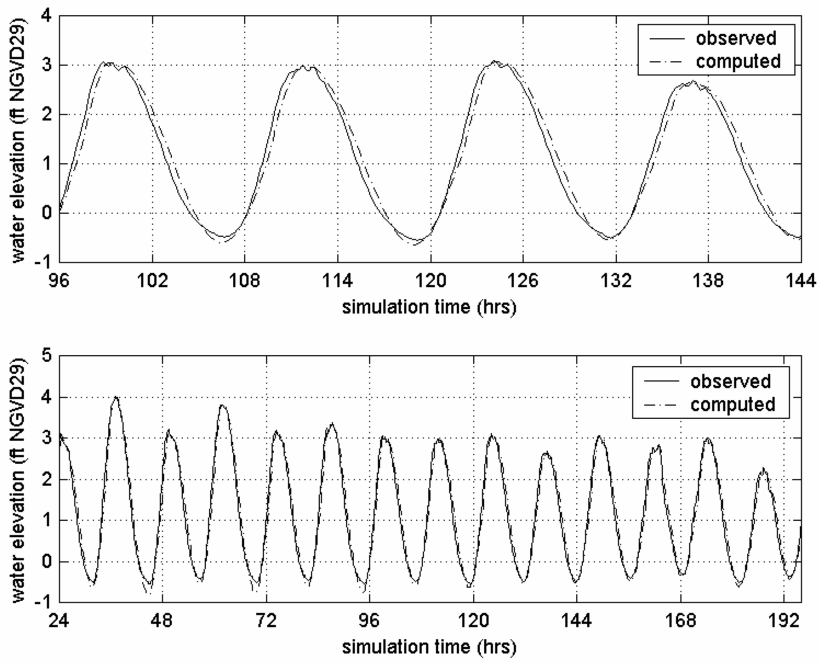

Figure V-50. Observed and computed water surface elevations during calibration time period, for Taylors Pond.

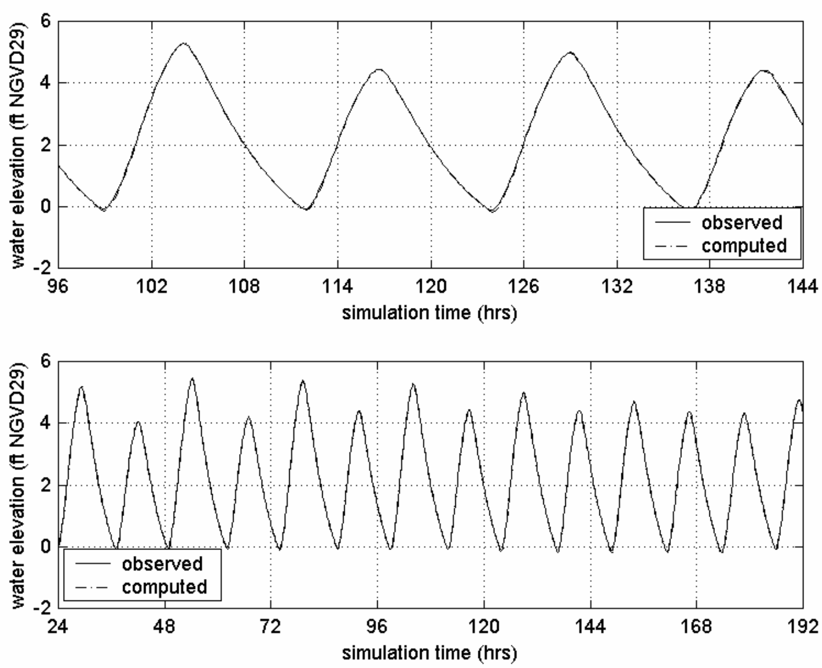

Figure V-51. Observed and computed water surface elevations during calibration time period, for Crows Pond.

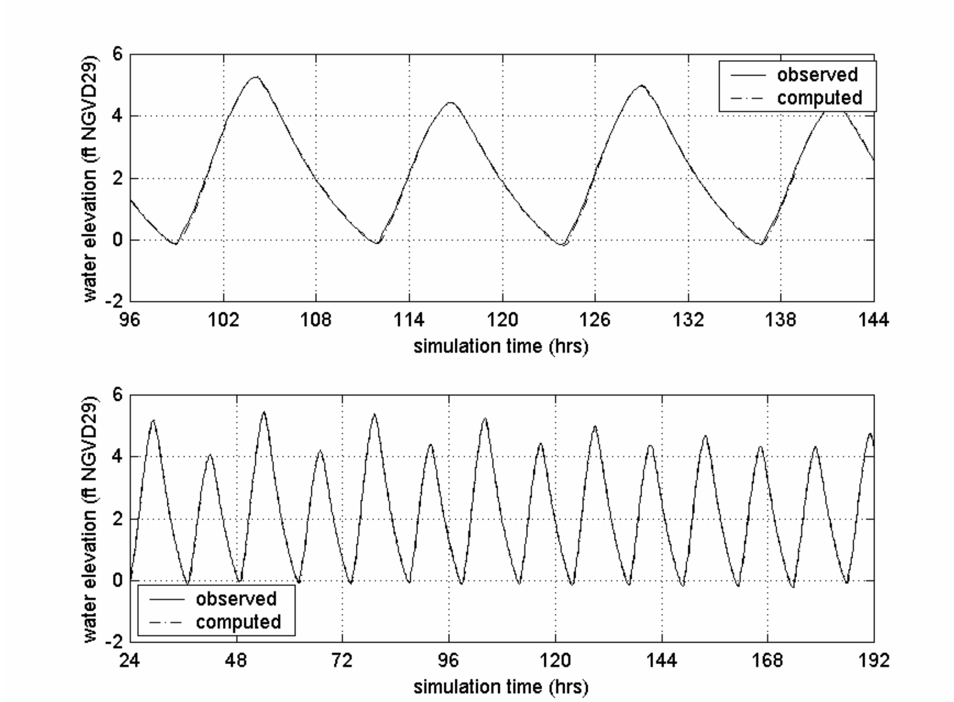

Figure V-52. Observed and computed water surface elevations during calibration time period, for Ryder Cove.

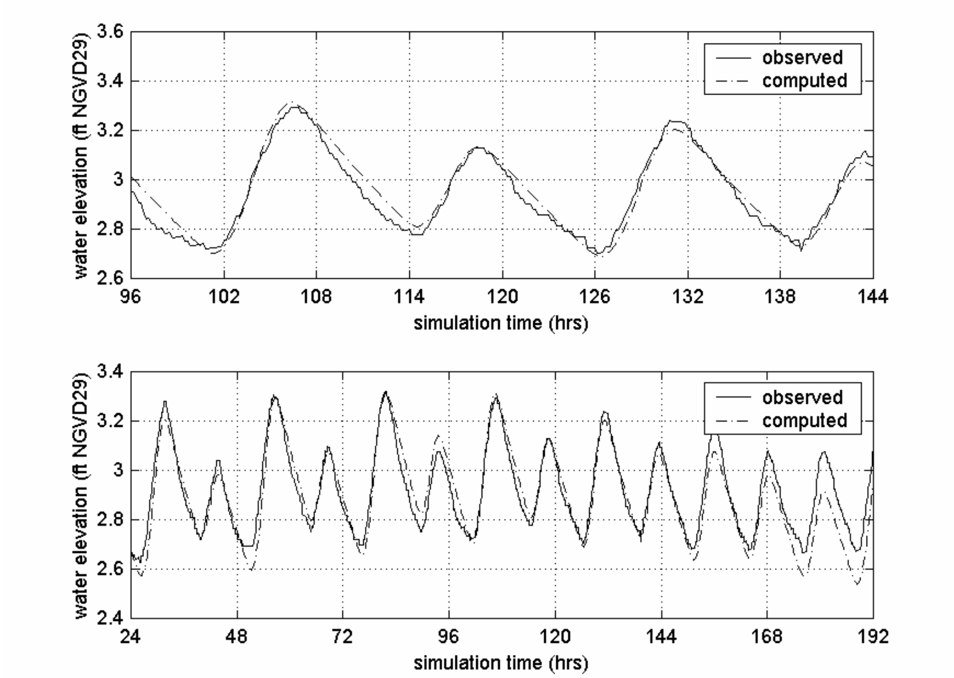

Figure V-53. Observed and computed water surface elevations during calibration time period, for Frost Fish Creek.

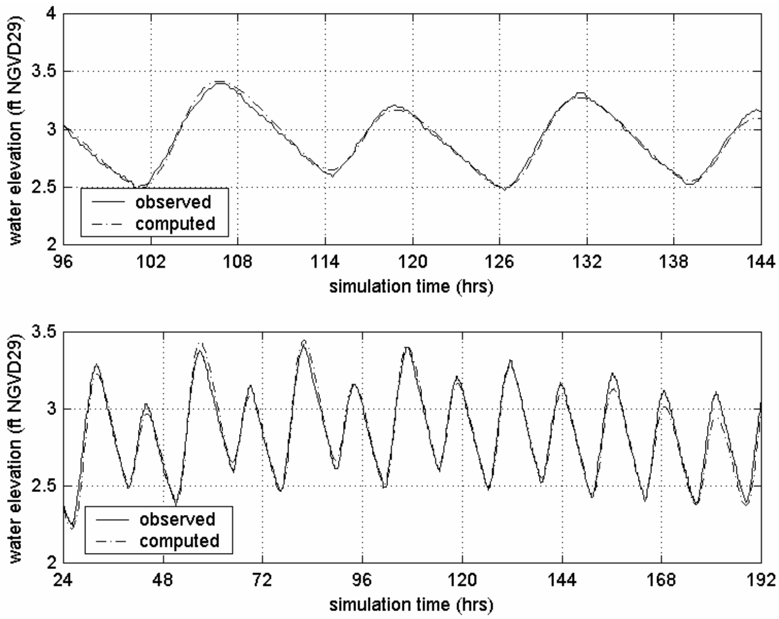

Figure V-54. Observed and computed water surface elevations during calibration time period, for Muddy Creek.

Table V-9. Tidal constituents for measured water level data and calibrated model output for northern embayments.						
Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	2.17	0.37	0.06	0.30	171.2	267.3
Ryder Cove	2.17	0.35	0.07	0.30	170.2	265.4
Frost Fish Creek	0.20	0.05	0.01	0.08	247.0	34.3
Muddy Creek	0.33	0.05	0.01	0.11	251.0	19.3
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	2.16	0.36	0.05	0.30	170.9	266.9
Ryder Cove	2.16	0.32	0.07	0.30	168.9	263.6
Frost Fish Creek	0.20	0.04	0.01	0.08	237.8	43.6
Muddy Creek	0.33	0.06	0.01	0.10	246.9	25.5
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	0.01	0.01	0.01	0.00	0.6	0.4
Ryder Cove	0.01	0.02	0.00	0.00	2.8	1.8
Frost Fish Creek	0.00	0.01	0.00	0.00	19.0	9.7
Muddy Creek	0.00	0.01	0.00	0.01	8.6	6.4

Table V-10. Tidal constituents for measured water level data and calibrated model output for Stage Harbor and South Coast Embayments.

Location	Constituent Amplitude (ft)				Phase (deg)	
Model calibration run						
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	2.24	0.13	0.12	0.57	140.6	81.0
Little Mill Pond	2.24	0.13	0.12	0.57	140.7	82.1
Oyster Pond	2.16	0.14	0.07	0.56	153.9	214.7
Sulphur Springs	1.40	0.23	0.03	0.48	171.7	278.3
Taylors Pond	1.80	0.18	0.06	0.16	152.4	245.7
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	2.30	0.13	0.13	0.57	142.4	85.7
Little Mill Pond	2.31	0.13	0.14	0.57	142.7	86.3
Oyster Pond	2.03	0.14	0.07	0.57	155.1	222.1
Sulphur Springs	1.35	0.28	0.05	0.48	164.6	277.8
Taylors Pond	1.82	0.14	0.04	0.17	149.3	243.2
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	**0.06**	0.00	0.01	0.00	3.7	4.9
Little Mill Pond	0.07	0.00	0.02	0.00	4.2	4.3
Oyster Pond	0.13	0.00	0.00	0.01	2.5	7.7
Sulphur Springs	0.05	0.05	0.02	0.00	14.8	0.4
Taylors Pond	0.02	0.04	0.02	0.01	6.5	10.5

The hydrodynamic model's ability to predict propagation of the secondary non-linear constituents through the estuary is important for understanding the attenuation of the tidal signal and the impact this has on estuarine circulation. Of primary interest is the M_4 constituent, which can be used to determine the flood dominance (sediment trapping characteristics) of an estuarine system. Proper prediction of M_4 provides confidence in the model's accuracy, since this indicates that the model is capable of simulating the tidal wave form and size. Similar to the model predictions for M_2, comparison of the information from Tables V-9 and V-10 indicates that the modeled phase of M_4 falls within one time step of the observed value.

V.4.3 Model Verification Using ADCP Measurements

The calibration procedure used in the development of the five separate finite-element models required a match between measured and modeled tides. To verify the performance of the Stage Harbor and Bassing Harbor models, computed flow rates were compared to flow rates measure using an ADCP. The ADCP data survey efforts are described in Chapter III. For model verification, both models were run for the period covered during each ADCP survey, on August 16 for Stage Harbor, and September 1 for Bassing Harbor. Model flow rates were computed in RMA-2V at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in each survey.

V.4.3.1 Stage Harbor

A comparison of the measured and computed volume flow rates at the Stage Harbor Inlet is shown in Figure V-55 in the top plot, and the tide curve for the same time period is shown in the lower plot. Each ADCP point is a summation of flow measured along the ADCP transect. The ‘bumps’ and ‘skips’ of the flow rate curve can be attributed to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlet, and in the harbor. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

Figure V-55 for the Stage Harbor inlet shows a remarkably good agreement with the model predictions. The calibrated model accurately describes the general conditions and the irregularities of the discharge through the Stage Harbor inlet. Again, at the mouth of Oyster Pond River (Figure IV-56) and the Mill Pond Bridge (Figure V-57), computed volume flow rates agree well with the field measurements, even though the flows are an order of magnitude (~10 times) smaller at the Mill Pond Bridge than in Stage Harbor. Currents are more difficult to accurately measure with the ADCP along the Mill Pond Bridge and Oyster Pond River transects, since these areas are considerably shallower than the harbor inlet. Therefore, portions of the channels are not covered by the ADCP because 1) the ADCP draft (no measurements in top layer), and 2) tide flats too shallow to safely navigate the survey boat, become a much more significant source of measurement error.

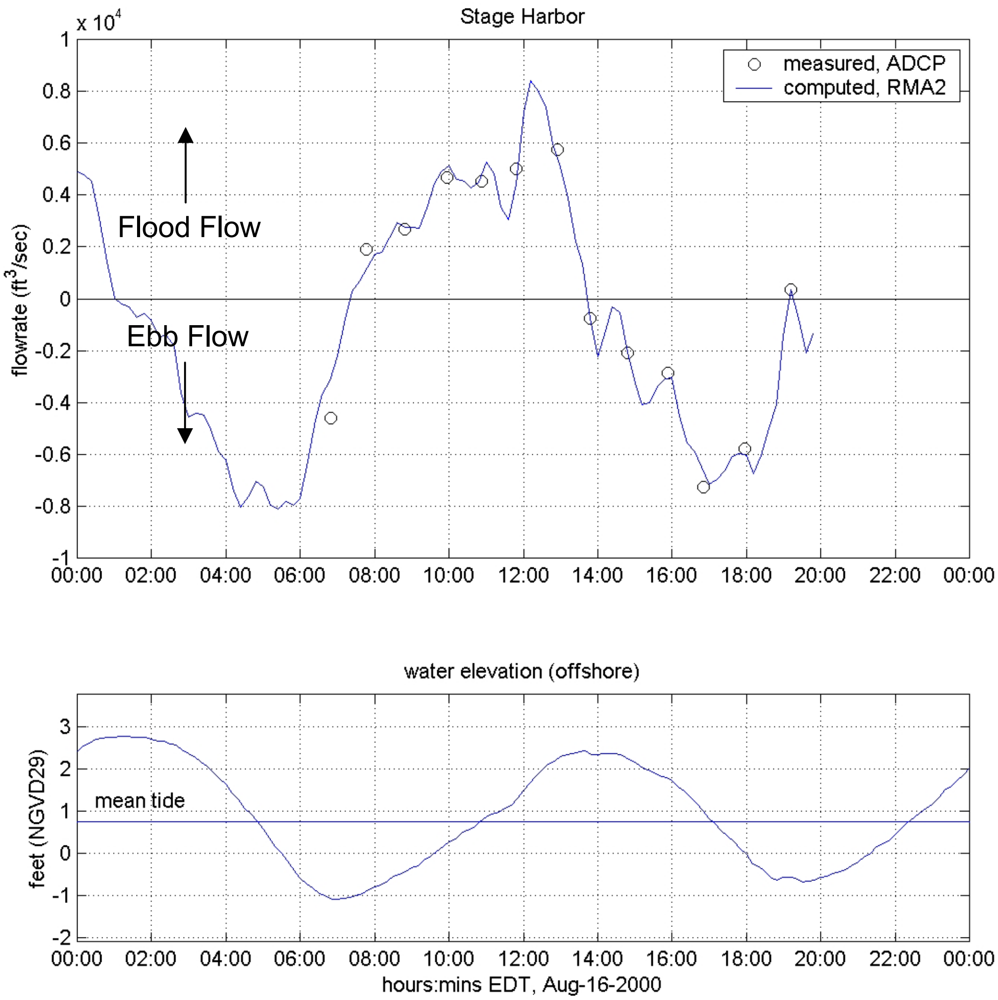

Figure V-55. Comparison of measured volume flow rates versus modeled flow rates through the Stage Harbor Inlet over a tidal cycle on August 16, 2000. Flood flows into the harbor are positive (+), and ebb flows out of the harbor are negative (-).

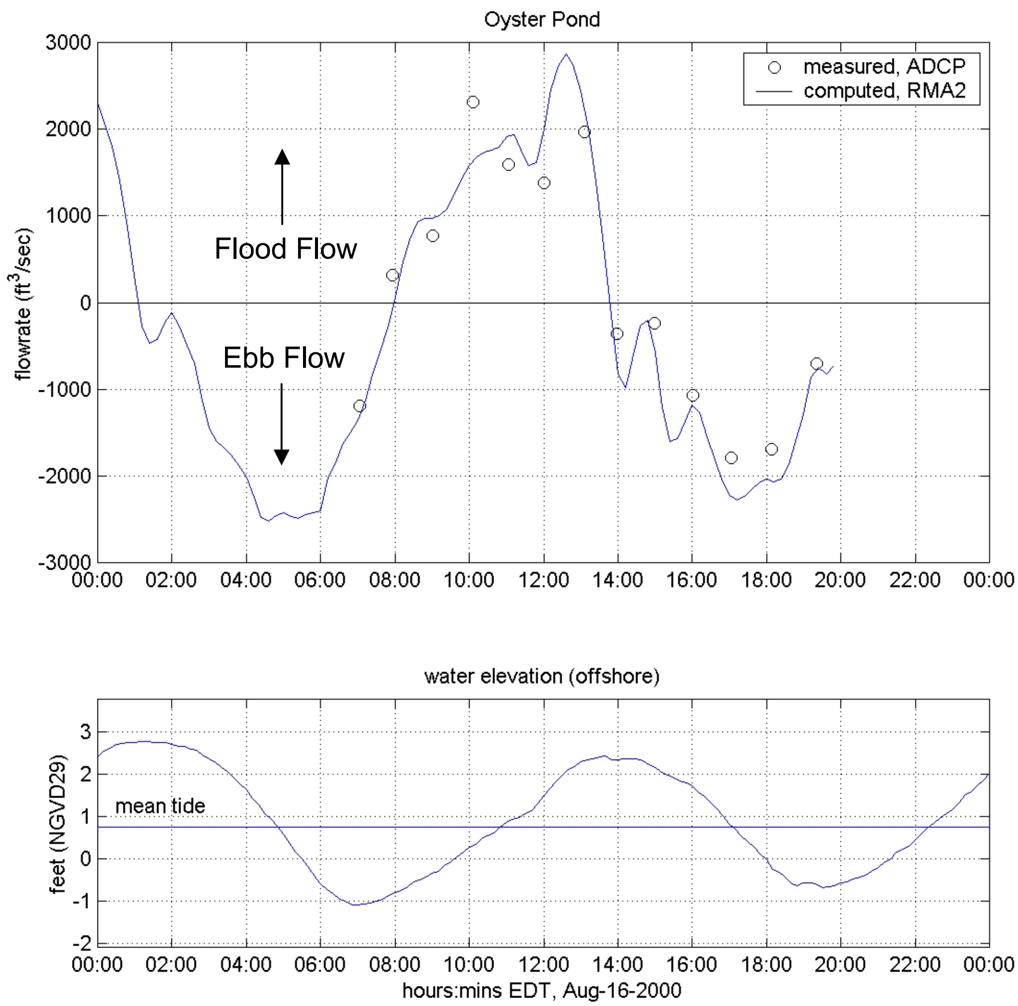

Figure V-56. Comparison of measured volume flow rates versus modeled flow rates through the mouth of Oyster Pond River over a tidal cycle on August 16, 2000. Flood flows into the river are positive (+), and ebb flows out of the river are negative (-).

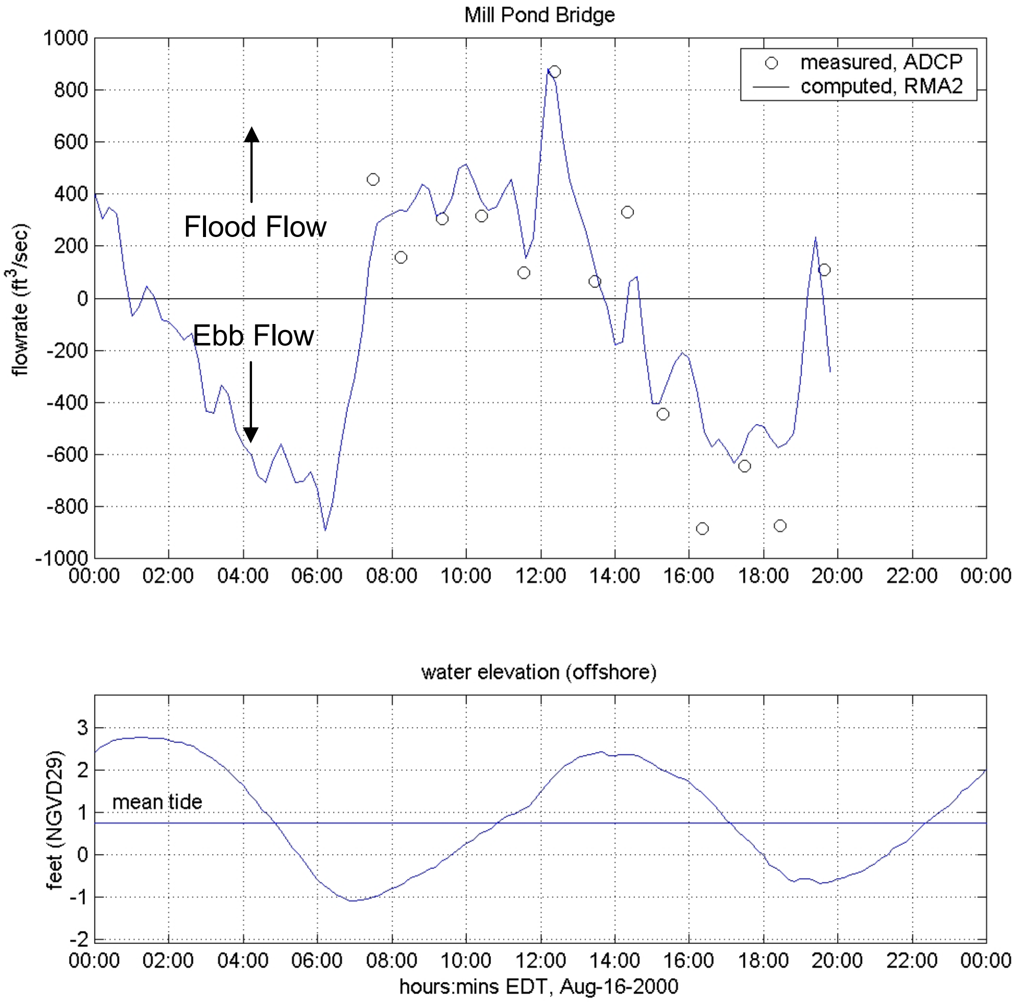

Figure V-57. Comparison of measured volume flow rates versus modeled flow rates through the Mill Pond Bridge over a tidal cycle on August 16, 2000. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-).

V.4.3.2 Bassing Harbor

The calibrated Bassing Harbor model was utilized to compute volume flow rates for the mouth of Bassing Harbor, Ryder Cove (including Frost Fish Creek), and Crows Pond. The overall shape of the volume flow curve at the entrance to Bassing Harbor is relatively smooth compared to the Stage Harbor curve, suggesting that wind had less influence on water level changes for this system during the survey period. Flow rates at the Bassing Harbor inlet were noticeably over-predicted during ebb flows (Figure V-58).

The apparent large difference (~20%) during ebbing flow may result from the fact that the ADCP survey transect at the mouth of Bassing Harbor crossed between the southern shore of the inlet and Fox Hill to the north, and not completely across the harbor entrance. Fox Hill is an island, and is connected to the northern shore of the harbor mouth by a sand spit, which is submerged during much of the tide cycle. During the period of the tide cycle following high tide, water can flow easily over this spit. However, during the period following low tide, the spit is barely submerged, resulting in much less flow in this area of the harbor mouth. Therefore, measured and modeled flow rates agree better during the flood flow, when nearly all the flow into Bassing Harbor occurs between Fox Hill and the southern shore of the harbor entrance.

Water moving through Bassing Harbor is divided between Ryder Cove/Frost Fish Creek and Crows Pond. The computed volume flow rates from the calibrated model closely reflect the measured flow rates in the sub-embayments of Bassing Harbor (Figure V-59 and V-60).

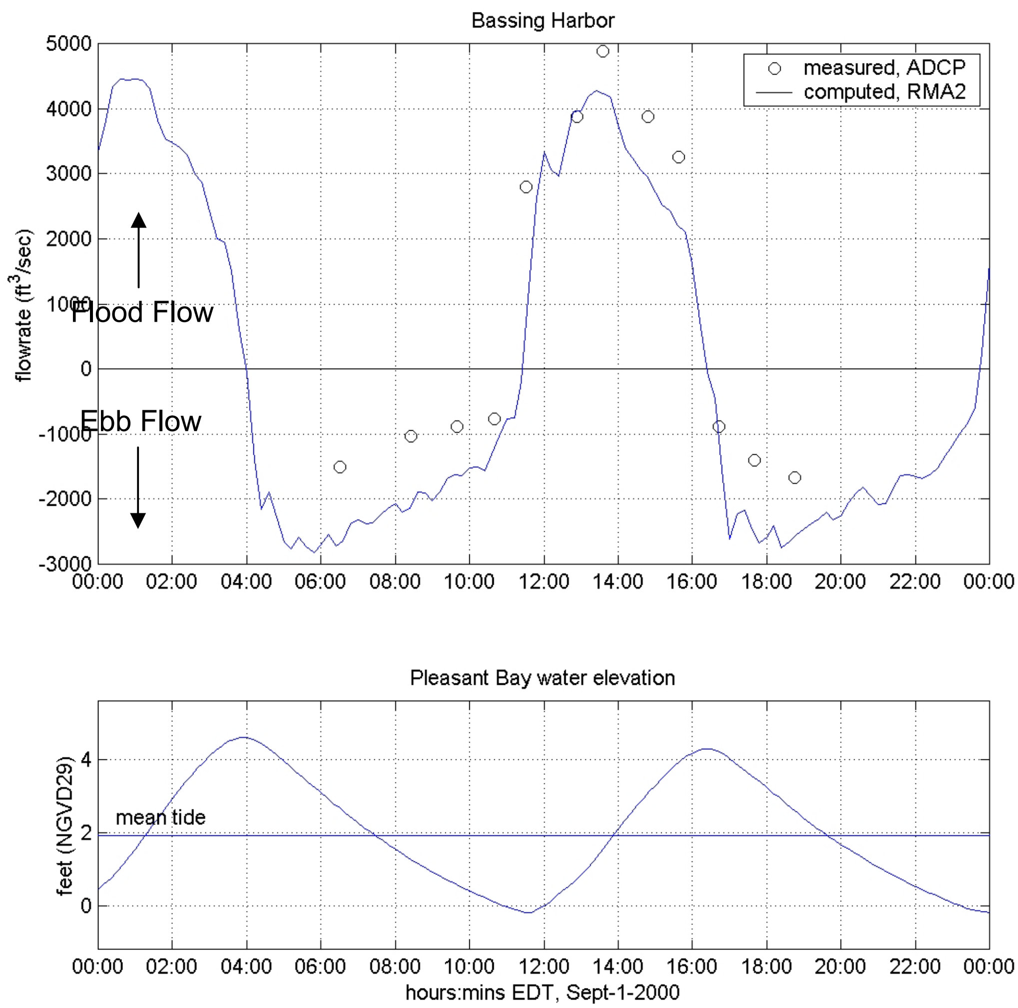

Figure V-58. Comparison of measured volume flow rates versus modeled flow rates through the Bassing Harbor Inlet over a tidal cycle on September 1, 2000. Flood flows into the harbor are positive (+), and ebb flows out of the harbor are negative (-).

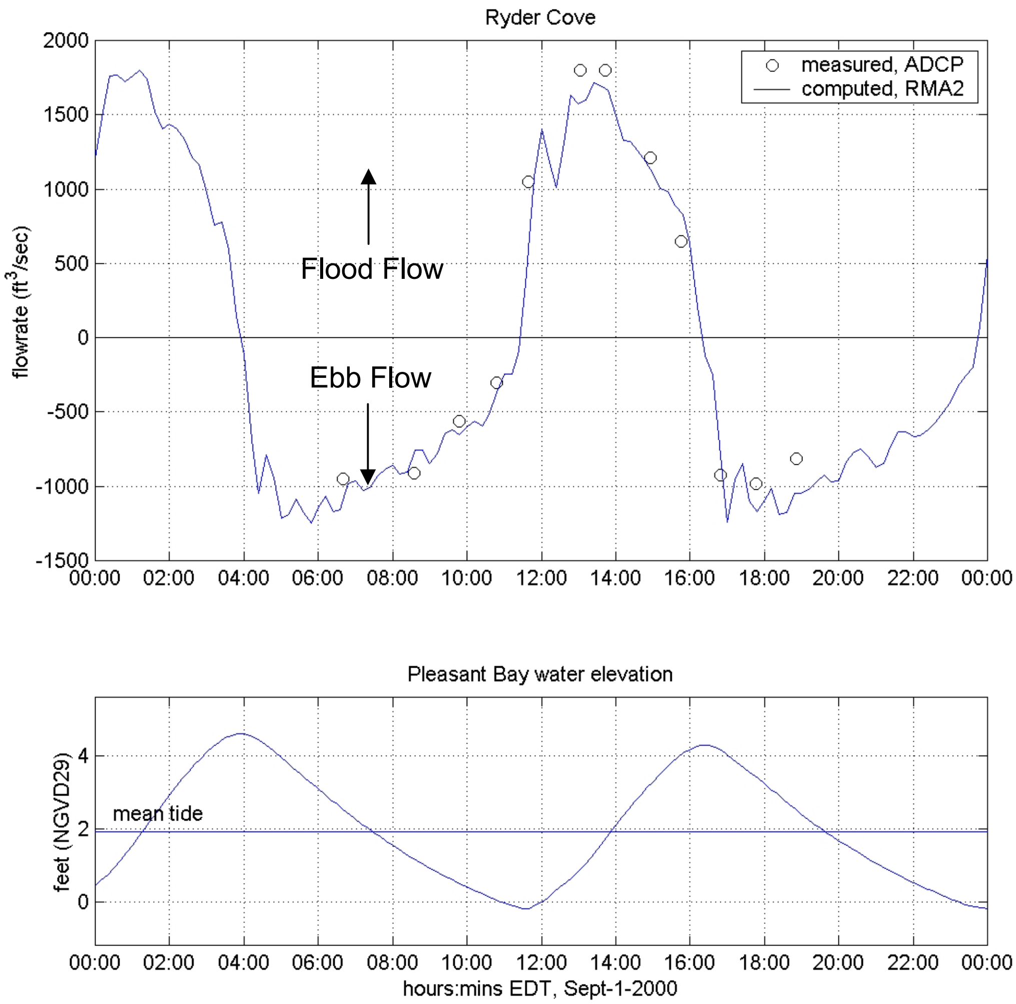

Figure V-59. Comparison of measured volume flow rates versus modeled flow rates through the entrance to Ryder Cove/Frost Fish Creek over a tidal cycle on September 1, 2000. Flood flows into the cove are positive (+), and ebb flows out of the cove are negative (-).

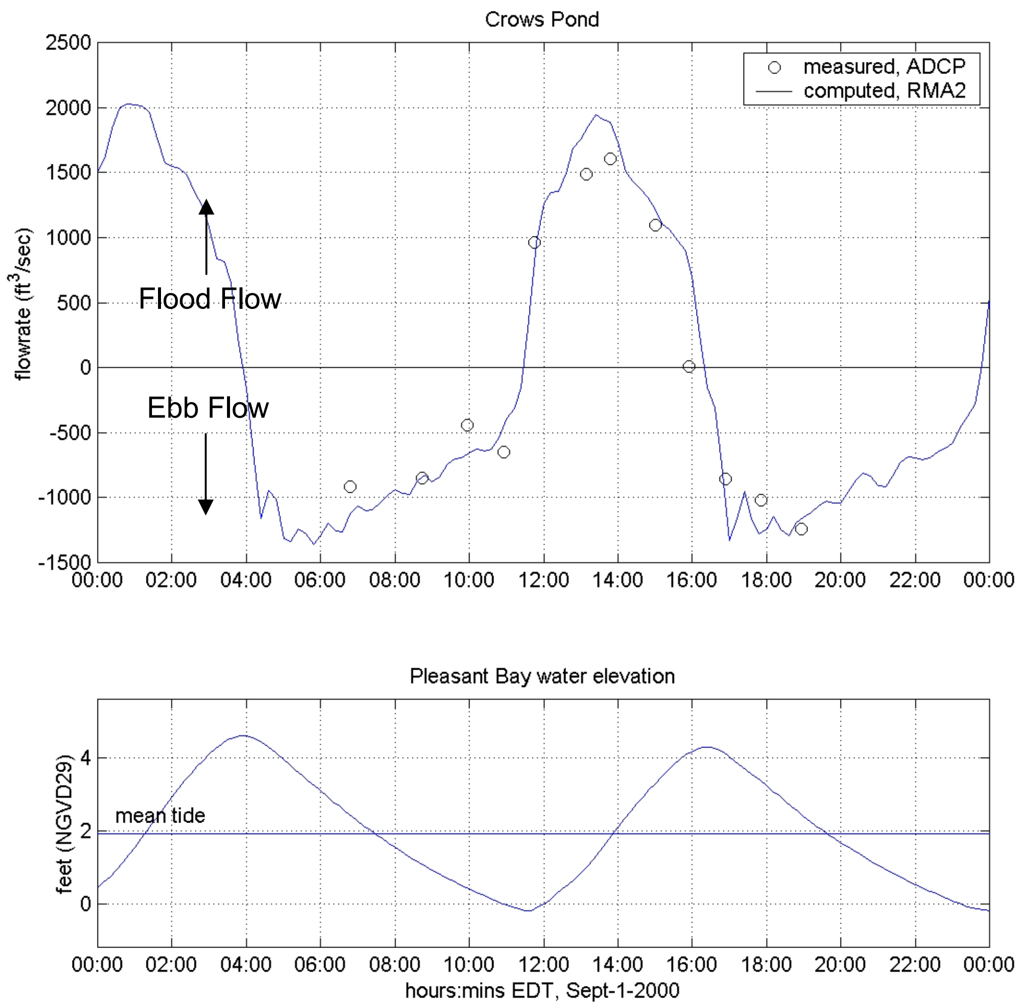

Figure V-60. Comparison of measured volume flow rates versus modeled flow rates through the mouth of Crows Pond over a tidal cycle on September 1, 2000. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-).

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within each of the modeled systems is tidal exchange. An exception in this study is Frost Fish Creek, where estimated groundwater inflow into the creek is slightly greater than 50% of the average tidal exchange through the Route 28 culverts, based on the average tidal flow 2.8 ft^3/sec (125,200 ft^3 per tide cycle) and estimated freshwater input of 1.6 ft^3/sec (annual average). A rising tide offshore in Nantucket Sound or Pleasant Bay creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, each estuary drains into the open waters of Nantucket Sound or Pleasant Bay on an ebbing tide. This exchange of water between each system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

V.5.1 Residence Times

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Crows Pond as an example, the **system residence time** is the average time required for water to migrate from Crows Pond, through Bassing Harbor, and into Pleasant Bay, where the **local residence time** is the average time required for water to migrate from Crows Pond to Bassing Harbor. Local residence times for each sub-embayment are computed as:

$$T_{local} = \frac{V_{local}}{P} t_{cycle}$$

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, **system residence times** are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. For the Stage Harbor Region estuaries this approach is applicable, since it assumes the main system has relatively low quality water relative to Nantucket Sound.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The future water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Stage Harbor System, South Coast Embayments, and Pleasant Bay Region estuaries.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in each estuary, model results were used to compute residence times. Residence times were computed for the entire estuary, as well as several sub-embayments within the estuary. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for each of the estuarine systems. Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Residence times were averaged for the tidal cycles comprising the representative 7.25 day period (14 tide cycles), and are listed in Table V-12. Model divisions used to define the system sub-embayments listed in Tables V-11 and V-12 are shown in Figures V-61 through Figure V-65, in the previous section. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume.

Generally, errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. Since the calibration period represented average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the various sub-embayments. The bathymetry data collection effort focused on regions of rapidly changing flow conditions (flow constrictions). This methodology provided an efficient and economical technique to measure bathymetric fluctuations affecting tidal flushing; however, the limited bathymetry survey associated with this study may have missed some shoals and/or deep holes introducing minor errors into the residence time calculations. In addition, limited topographic measurements were available on the extensive marsh plains of the South Coast Embayments.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift along the Nantucket Sound and Pleasant Bay shorelines in Chatham typically is strong and local winds induce tidal mixing within the regional estuarine systems, the “strong littoral drift” assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the “strong littoral drift” assumption are within 10% to 15% of “true” residence times.

Table V-11. Embayment mean volumes and average tidal prism during simulation period.

System	Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Stage Harbor	Stage Harbor (system)	142,825,500	107,176,900
	Mitchell R. / Upper Stage H.	40,210,100	20,729,200
	Mill Pond	19,067,900	8,349,300
	Little Mill Pond	3,394,400	1,312,400
	Oyster Pond River	42,797,000	35,598,500
	Oyster Pond	28,218,000	17,925,400
Sulphur Springs	Bucks Creek (system)	7,426,200	10,311,800
	Sulphur Springs	4,885,700	6,747,900
	Cockle Cove Creek	818,700	1,133,200
Taylors Pond	Mill Creek (system)	6,973,900	9,341,300
	Taylors Pond	3,145,600	2,003,100
Bassing Harbor	Bassing Harbor (system)	102,152,200	51,252,700
	Crows Pond	53,345,200	20,699,300
	Ryder Cove	19,385,600	12,805,800
	Frost Fish Creek	1,414,500	1,230,000
	Upper Frost Fish Creek	727,800	125,200
	Ryder Cove / Frost Fish Creek	30,338,500	18,967,900
Muddy Creek	Muddy Creek (system)	5,699,300	982,900

The relatively long residence time for a sub-embayment such as Cockle Cove Creek reveals the inadequacy of using system residence time alone to evaluate water quality. The system residence time is computed as 3.4 days, even though this marsh creek nearly goes dry at low tide. By the definition of system residence time, smaller sub-embayments have longer residence times; therefore, residence times may be misleading for small, remote parts of the estuary. Instead, it is useful to compute a local residence time for each sub-embayment. A local residence time represents the time required for a water parcel to leave the particular sub-embayment. For instance, the local residence time for Upper Frost Fish Creek represents the time required for a water parcel to be flushed from the upper portion of the creek into lower Frost Fish Creek. Local residence times are computed as the volume of the sub-embayment divided by the tidal prism of that sub-embayment, and units are converted to days. Table V-12 lists local residence times for several areas within each of the modeled systems.

Local residence times in Table V-12 are significantly lower than residence times based on the volume of the entire estuary. For example, flow entering Little Mill Pond on an average tidal cycle flushes through Stage Harbor inlet in 56.3 days, but flushes into Mill Pond in 1.3 days. Generally, a local residence time is only useful where the adjacent embayment has high water quality. For some of the embayments located in the upper reaches of each system (again, Mill

Pond and Frost Fish Creek), the receiving waters that exchange tidal flow with the various sub-embayments show signs of ecological stress, indicative of poor water quality. Therefore, system residence times may be more appropriate for future planning scenarios.

Table V-12. System and Local residence times (flushing rates) for Chatham sub-embayments.

System	Embayment	System Residence Time (days)	Local Residence Time (days)
Stage Harbor	Stage Harbor (system)	0.7	0.7
	Mitchell R. / Upper Stage H.	3.6	1.0
	Mill Pond	8.9	1.2
	Little Mill Pond	56.3	1.3
	Oyster Pond River	2.0	0.6
	Oyster Pond	4.1	0.8
Sulphur Springs	Bucks Creek (system)	0.4	0.4
	Sulphur Springs	0.6	0.4
	Cockle Cove Creek	3.4	0.4
Taylors Pond	Mill Creek (system)	0.4	0.4
	Taylors Pond	1.8	0.8
Bassing Harbor	Bassing Harbor (system)	1.0	1.0
	Crows Pond	2.6	1.3
	Ryder Cove	4.1	0.8
	Frost Fish Creek	43.0	0.6
	Upper Frost Fish Creek	422.3	3.0
	Ryder Cove / Frost Fish Creek	2.8	0.8
Muddy Creek	Muddy Creek (system)	3.0	3.0

Another important characteristic of system residence times is that values determined for each sub-embayment are directly dependent on what exactly the total system volume includes. This is readily apparent when a comparison of system residence time from the current report is made to values presented in previous flushing calculations for all of Pleasant Bay (ACI, 1997). For example, in the present study the system residence time for Crows Pond (in the Bassing Harbor system) is calculated to be *2.6* days, but from the earlier study the system residence time for Crows Pond is *68.6* days. The difference is due to the different system volumes used to compute each numbers, i.e., only the volume of the Bassing Harbor system (102,152,200 ft^3) in this study, and the volume of the entire Pleasant Bay (1,997,780,000 ft^3) for the earlier study. Alternatively, local residence times from these two studies show much closer agreement (1.3 days and 1.8 days, for this study and ACI, 1997 respectively), because these numbers are based on the volume of the same sub-embayment, Crows Pond in this case.

V.5.2 Pre-Breach Conditions

The formation of New Inlet in 1987 altered the hydrodynamics within the Pleasant Bay Estuary. As a result of the inlet, the tide range in Pleasant Bay has increased by approximately 1 ft, with a corresponding improvement to tidal flushing within the northern portions of the estuary. The inlet continues to migrate south and Nauset Beach will return to a morphology similar to the pre-breach form. This pattern of inlet formation and southerly growth of Nauset Beach is cyclical. The two most recent breaches through the Nauset barrier occurred in 1846 east of Allen Point and 1987 east of the Chatham Lighthouse. The anticipated cyclical behavior of the inlet system is based on the work of Geise (1988) who described the historical 1846 breach and the subsequent re-formation of Nauset Beach during the following 140 years. For comparison purposes, the pre-breach 1970's form of Nauset Beach is shown in Figure V-61 and the more efficient 1996 system is shown in Figure V-62.

The modeling effort presented above was performed for the existing (post-breach) conditions based on recently obtained bathymetric and tidal data, as well as information from a previous study of regional hydrodynamics (ACI, 1997). To simulate pre-1987 conditions when the Chatham Harbor/Pleasant Bay system was less hydraulically efficient, a revised model grid was developed as part of this previous modeling effort to simulate the pre-breach estuary (ACI, 1997). As a basis for the model grid, digital data obtained from historic NOAA surveys of the region were utilized to supplement the 1997 bathymetry data. Due to the orientation of the historic inlet, the pre-breach estuary was served by a combination of tides from the Atlantic Ocean and Nantucket Sound. The modeling analysis for the pre-breach estuary utilized Atlantic Ocean tides only (the measured 1997 Atlantic Ocean tide data was used to drive the model); however, an attempt was made to "calibrate" the model to the predicted amplitude damping and phase lags presented in the pre-breach NOAA Tide Tables.

To "calibrate" the pre-breach model, ACI matched the modeled tides to the historic amplitude damping and phase lag presented in the 1986 NOAA Tide Tables. For example, the mean tide range in the Atlantic Ocean offshore of Chatham was predicted to be 6.7 ft, with the tide range reducing to 3.6 ft in Chatham Harbor and 3.2 ft in Pleasant Bay. In general, the modeled pre-breach conditions compared well with the NOAA tide information.

The less efficient pre-breach inlet causes the mean tide range within the system to be reduced by approximately 1 ft (ACI, 1997). The reduction in tide range has a corresponding reduction in flow velocities and volume of water moved through the estuary and its sub-embayments. Pre-breach hydrodynamic characteristics were computed utilizing the models developed for Chatham's Pleasant Bay embayments, and a forcing tide generated from the ACI 1997 pre-breach model scenario. Figure V-63 shows the predicted 1997 Pleasant Bay tide, with the corresponding tide curves for the Bassing Harbor system and Muddy Creek developed as part of this study. A calculation of residence times was performed to evaluate the magnitude of the worst-case pre-breach scenario on tidal flushing. The results of this analysis are shown in Tables V-13 and V-4.

The information presented in Tables V-14 and V-15 indicates between a 10% and 88% increase in residence times for the sub-embayments within the Pleasant Bay Estuary. For most of the estuary, the increase in residence times was between 50% and 70%. There are two primary causes for the substantial increase in residence times for the Pleasant Bay systems: 1) an increase in mean sub-embayment volumes for pre-breach conditions, and 2) reduction in the tide range.

Figure V-61. Topographic map from the 1970's indicating the pre-breach inlet between Morris Island and Nauset Beach.

Figure V-62. Recent nautical chart indicating the location of New Inlet at the breach in Nauset Beach

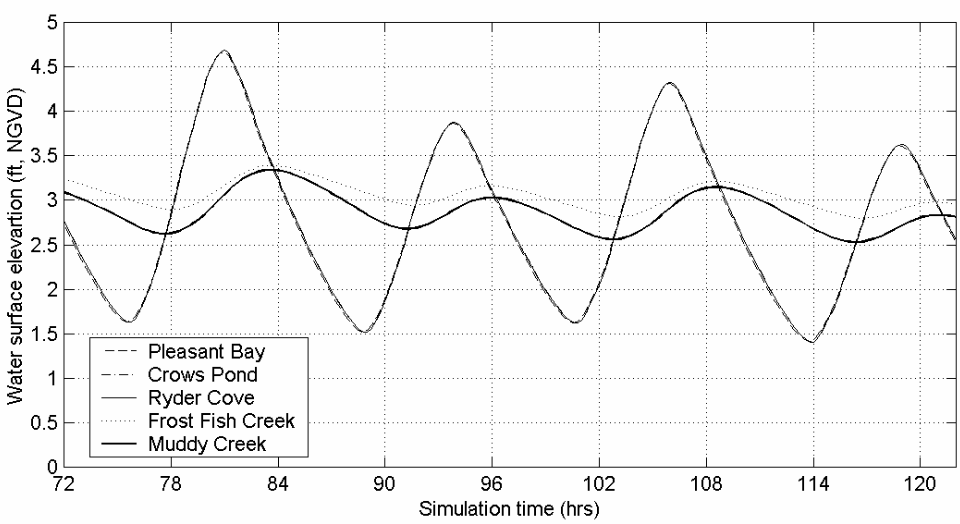

Figure V-63. Plot of two tide cycles of model run results for pre-breach conditions at Muddy creek and Bassing Harbor sub-embayments.

Table V-13. Embayment mean volumes and average tidal prism during simulation period for modeled pre-breach conditions in Pleasant Bay.

System	Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Bassing Harbor	Bassing Harbor (system)	114,689,900	33,724,000
	Crows Pond	58,302,100	13,602,600
	Inner Ryder Cove	22,267,400	8,437,200
	Frost Fish Creek	1,744,700	898,300
	Upper Frost Fish Creek	768,600	119,021
	Ryder Cove / Frost Fish Creek	34,894,300	12,442,600
Muddy Creek	Muddy Creek (system)	6,496,875	870,315

Table V-14. System and Local residence times (flushing rates) for Pleasant Bay sub-embayments for modeled pre-breach conditions.

System	Embayment	System Residence Time (days)	Local Residence Time (days)
Bassing Harbor	Bassing Harbor (system)	1.8	1.8
	Crows Pond	4.4	2.2
	Inner Ryder Cove	7.0	1.4
	Frost Fish Creek	66.1	1.0
	Upper Frost Fish Creek	498.7	3.3
	Ryder Cove / Frost Fish Creek	4.8	1.5
Muddy Creek	Muddy Creek (system)	3.9	3.9

Table V-15. Percent change in residence times from present conditions for Pleasant Bay sub-embayments for modeled pre-breach conditions.

System	Embayment	System Residence Time change (%)	Local Residence Time change (%)
Bassing Harbor	Bassing Harbor (system)	80.0	80.0
	Crows Pond	69.2	69.2
	Inner Ryder Cove	70.7	75.0
	Frost Fish Creek	53.7	66.7
	Upper Frost Fish Creek	18.1	10.0
	Ryder Cove / Frost Fish Creek	71.4	87.5
Muddy Creek	Muddy Creek (system)	30.0	30.0

The sub-embayment mean volumes change due to the increased pre-breach mean tide level (approximately 2.1 ft NGVD for present conditions, and 3.1 ft NGVD for pre-breach conditions, from Table V-16). The reduction in tide range is the greatest of the two factors affecting flushing rates. Table V-16 shows mean-high-water and mean-low-water datums for pre- and post-breach conditions. The post-breach datums were computed using the TDR data collected in August and September 2000 for Ryder Cove. High water levels are similar, but low water levels differ by about 1 ft, therefore the mean tide range of the pre-breach condition is only about 68% of the mean tide range measured in this study. Finally, system and local residence times for each sub-embayment change by different percentages because the change in mean sub-embayment volumes verses mean system volumes is not equivalent. For example, the mean volume of the entire Bassing Harbor System (use for computing system residence times for all sub-embayments in the system) increases by 12% for pre-breach conditions, but the mean volume of Inner Ryder Cove (used to compute local residence time for Inner Ryder Cove) increases by 15%.

Within Muddy Creek, an anticipated increase in residence time of 30% is predicted by the model for the pre-breach conditions. Since the tide range within Pleasant Bay is reduced by approximately 1 ft for pre-breach conditions, the tidal exchange is greatly retarded through the Route 28 culverts. Larger culverts would allow better exchange of tidal waters between Muddy Creek and Pleasant Bay would limit the anticipated increase in residence times as the estuary returns to a pre-breach morphology.

Table V-16. Comparison of tide datums and mean tide levels for pre- and post-breach conditions, for Inner Ryder Cove. Elevations are relative to NGVD 29. Datums for present conditions were computed using TDR data collected in August and September 2000 in Ryder Cove.

Frost Fish Creek	Mean High Water (ft)	Mean Low Water (ft)	Mean Tide Level (ft)
Present conditions	4.2	0.0	2.1
Pre-breach conditions	4.5	1.7	3.1

V.6 ALTERNATIVES TO IMPROVE TIDAL FLUSHING

The two sub-embayments linked to the Pleasant Bay estuary by culverts (Muddy Creek and Frost Fish Creek) exhibit relatively poor tidal flushing. Water quality improvements to these systems likely can be achieved through either resizing of culverts or turning upper portions of the coastal embayments into freshwater ponds. Evaluation of potential alternatives is critical to achieve water quality goals, as well as to avoid adverse environmental impacts.

The hydrodynamic models utilized to evaluate tidal flushing provide the basis for *quantitatively* analyzing the effects of various alternatives on tidal exchange. Using the calibrated models for each system, the model grids were modified to reflect alterations in culvert dimensions and/or bathymetry. Numerical models provided a cost-effective means for evaluating several water quality improvement scenarios. Incorporating hydrodynamic and water quality models was utilized to streamline the alternative selection process.

V.6.1 Muddy Creek

The two culverts running under Route 28 at Muddy Creek each have a height of approximately 2.6 feet and a width of 3.7 feet. Since the surface area of Muddy Creek is relatively large, these culverts are not of sufficient size to allow complete tidal exchange between Pleasant Bay and Muddy Creek. This poor tidal exchange is likely responsible for the water quality concerns for the Muddy Creek system. In addition, replacement of these culverts will likely be an expensive alternative due to the large roadway embankment overlying the flow control structures.

Due to the elevation of Route 28 in this region, the roadway embankment prevents storm surge from overtopping the road and “shocking” the ecosystem in Muddy Creek with a pulse of higher salinity Pleasant Bay water. Therefore, turning Muddy Creek into a completely freshwater system is a viable alternative. Other alternatives considered include turning a portion of the system to freshwater and enlarging the culverts to improve tidal exchange.

V.6.1.1 Alternative M1 – Muddy Creek as a Freshwater System

Gates could be installed on the Pleasant Bay end of the existing culverts to convert the estuarine system to completely freshwater. As mentioned above, the Route 28 embankment would prevent floodwaters from overtopping the road; therefore, the freshwater ecosystem would remain stable during severe conditions. The gates would allow only unidirectional flow from Muddy Creek into Pleasant Bay. Periodic maintenance of the culvert gates would be required, due to their open exposure within Pleasant Bay. A potential environmental drawback to this alternative is the loss of salt marsh that exists within approximately the northern third of the estuary. Since this alternative would eliminate tidal exchange between Muddy Creek and Pleasant Bay, no modeling was performed to evaluate the effect of the gates on local hydrodynamics.

V.6.1.2 Alternative M2 – Muddy Creek as a Partial Freshwater System

To preserve the salt marsh in the lower portion of Muddy Creek and improve tidal flushing characteristics without altering the culvert configuration, a dike could be placed approximately ½ mile upstream from the roadway embankment (see Figure V-64). The region upstream of the dike would be maintained as a freshwater pond, again with a gate that only allowed unidirectional flow from the upper portion of Muddy Creek to the lower estuarine portion. Since the poor tidal exchange through the existing culverts is caused by the small cross-sectional area of the culverts relative to the surface area of Muddy Creek estuary, reducing the estuarine surface area will improve flushing characteristics. For example, hydrodynamic model simulations of dike placement as shown in Figure V-64, reduces the mean-tide estuarine volume by 55%; however, it causes very little reduction in tidal prism. The increase in tide range resulting from Alternative M2 is shown in Figure V-65. In addition, a comparison of tidal flushing improvements is shown in Table V-17.

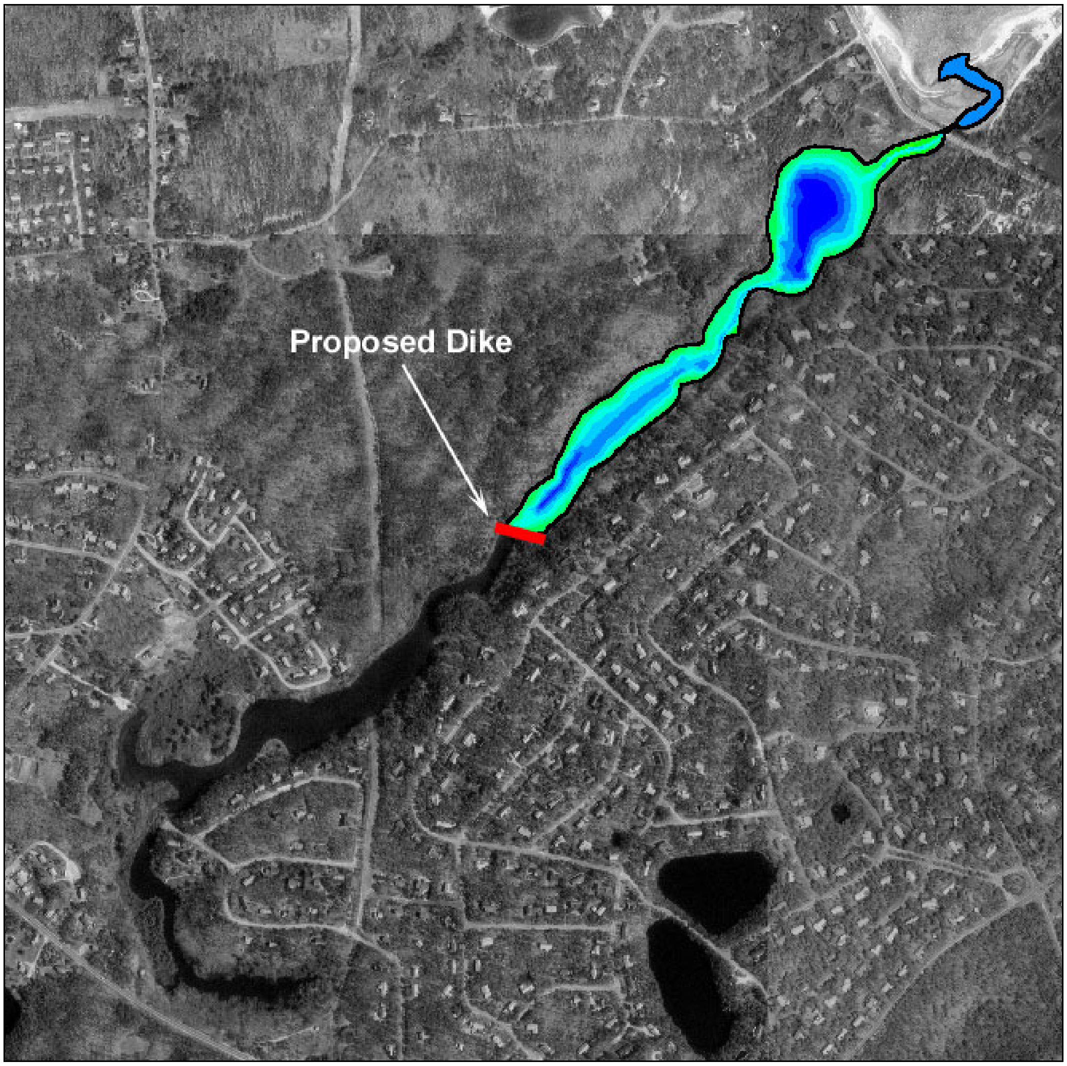

Figure V-64. Muddy Creek Alternative M2 illustrating the approximate position of the dike separating the freshwater and brackish regions.

Design considerations for the dike should include sufficient elevation to minimize potential overtopping during storm conditions. In addition, the freshwater pond level should be set at least 1.0 feet above the anticipated mean tide level in the estuarine section (about 3.5 feet NGVD according to Figure V-64) to ensure flow exits the freshwater section during all phases of the tide. A simple adjustable weir could be designed to fine-tune the water elevation in the freshwater section.

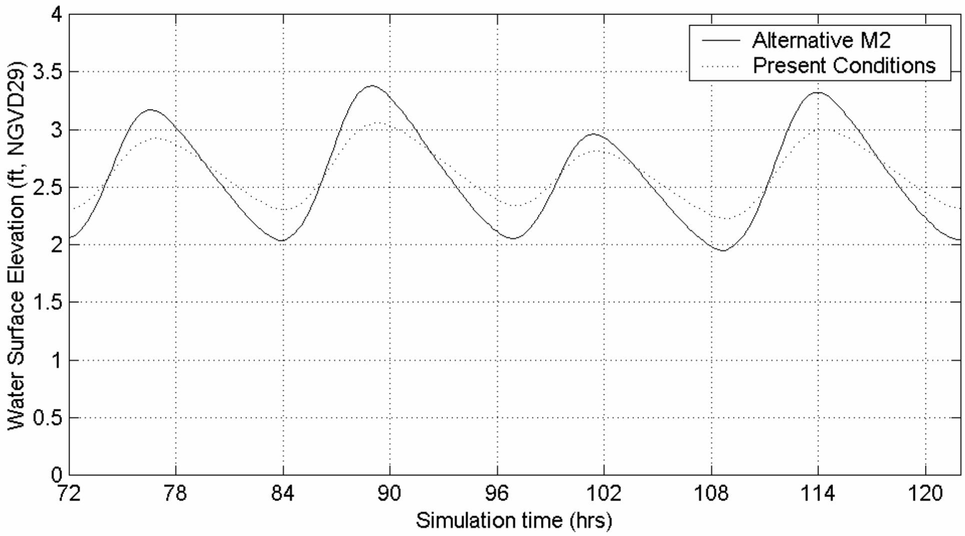

Figure V-65. Modeled tide range for Alternative M2 compared with present conditions.

V.6.1.3 Alternatives M3 and M4 – Increase Size of Route 28 Culverts

Although the Muddy Creek culverts are in good structural shape, it is possible that the Massachusetts Highway Department would consider culvert upgrading as part of the planned Route 28 improvements, if it clearly can be demonstrated that larger culverts are necessary to improve water quality. To assess tidal flushing improvements associated with larger culverts, two alternative culvert sizes were considered: a width of 8 feet and a width of 16 feet. Unlike the existing culverts, the culverts would be designed with a height similar to the tide range in Pleasant Bay (approximately 4.5 feet) to prevent the additional frictional drag associated with totally submerged culverts.

Table V-17 illustrates the change in tidal flushing associated with the two culvert alternatives. The smaller culvert alternative (Alternative M3) provided a similar tide range to Alternative M2. However, the residence time for Alternative M3 is similar to existing conditions, since the tidal prism increases by only about 20% and the mean-tide volume remains similar. Though the larger culvert alternative (Alternative M4) provided a significantly larger tide range, the reduction in residence time was not significantly greater than Alternative M2. The tidal curves for Alternatives M3 and M4 relative to existing conditions are shown in Figure V-66.

Table V-17. Comparison of system volume, tide prism, and residence tides for Muddy Creek for alternatives M2, M3, and M4.

Muddy Creek	system mean volume (ft^3)	tide prism volume (ft^3)	local residence time (days)
Present conditions	5,699,300	982,900	3.0
Alternative M2	3,150,700	957,500	1.7
Alternative M3	5,573,700	1,170,300	2.5
Alternative M4	5,404,600	2,816,100	1.0

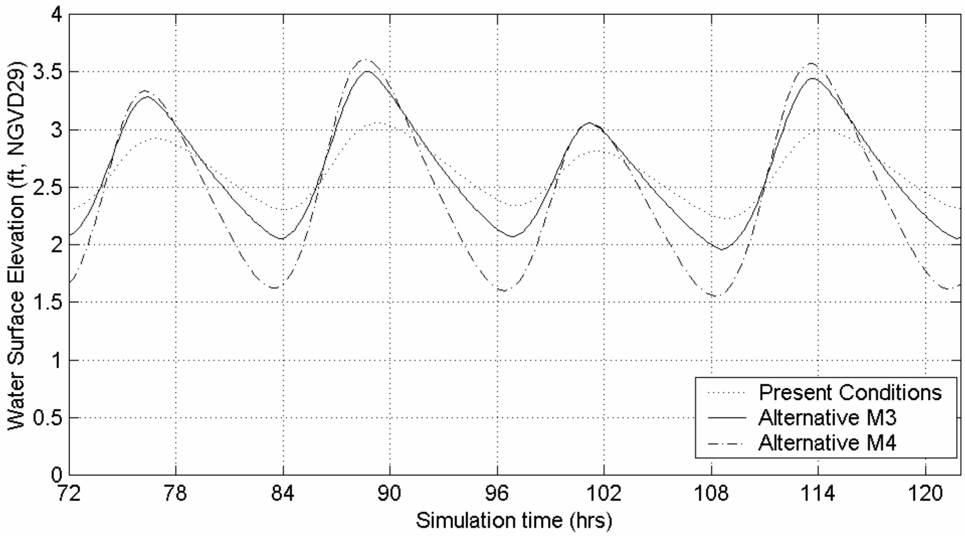

Figure V-66. Modeled tide range for Alternatives M3 and M4 compared with present conditions.

V.6.2 Frost Fish Creek

Two types of flow control structures exist at Frost Fish Creek. First, three partially-blocked 1.5 feet diameter culverts run under Route 28. Approximately 100 feet upstream of these culverts, a single large culvert and a dilapidated weir structure maintain the Creek level well above the mean tide elevation in adjoining Ryder Cove. Since the weir structure likely maintained Frost Fish Creek as a freshwater system, the culverts were adequate for handling the freshwater outflow from the Frost Fish Creek watershed. Following removal of the weir boards, Frost Fish Creek became a salt marsh system with a tide range of less than 0.5 feet. Similar to Muddy Creek, the size of the culverts limits tidal exchange with Ryder Cove and the rest of the Pleasant Bay estuary. The poor tidal exchange is likely responsible for the water quality concerns within Frost Fish Creek.

Since Route 28 in the vicinity of the creek culverts is below the predicted 100-year storm level, occasional overtopping of the roadway is anticipated. If the pond were maintained as a freshwater system, flooding would cause episodic increases in the pond salinity level, with the associated environmental impacts to wetland species. In addition, Frost Fish Creek presently supports a relatively healthy salt marsh system that would be destroyed by converting the system to freshwater. For these reasons, conversion of Frost Fish Creek back to a freshwater pond does not appear to be a feasible alternative. Instead, culvert options were considered to improve tidal exchange and enhance the existing salt marsh.

Since the existing culverts are partially clogged, the Massachusetts Highway Department has indicated a willingness to improve these structures as part of proposed work along Route 28. Two culvert alternatives were evaluated with the hydrodynamic model: Alternative F1 increased the tide range upstream of Route 28 to approximately 1.0 feet by installing a box culvert with a width of 5 ft and a height that allows the top of the culvert to remain above the water surface under most conditions; and Alternative F2 increased the tide range to approximately 1.5 feet by installing a box culvert with a width of 7 ft and a height that again allows the top of the culvert to remain above the water surface. An increase in tide range of greater than 1.5 feet may result in negative impacts to the marsh, because a greater portion of the marsh will be more frequently inundated with salt water; therefore, alternatives with larger culverts were not modeled. However, it may be feasible to reconstruct the weir upstream of Route 28 and utilize this structure to control tidal exchange and water elevations. Adjustment of the weir boards would allow “fine tuning” of the tide range within Frost Fish Creek. In this manner, culverts larger than those presented in Alternatives F1 and F2 below could be installed without impacting the marsh system.

Table V-18 illustrates the change in tidal flushing associated with the two culvert alternatives. The smaller culvert alternative (Alternative F1) provided a tide range of about 1.0 feet, with a significantly reduced local residence time of 1.3 days. The larger culvert alternative (Alternative F2) provided approximately a 1.5 ft tide range, as well as a lower residence time than Alternative F1. The tidal curves for Alternatives F1 and F2 relative to existing conditions are shown in Figure V-67. Due to the substantial tidal attenuation caused by the existing (partially blocked) culverts, the model indicated installation of larger culverts would significantly reduce the mean tide level with a negligible increase in the high tide elevation.

Table V-18. Comparison of system volume, tide prism, and residence tides for Frost Fish Creek for alternatives F1 and F2.

Frost Fish Creek	system mean volume (ft^3)	tide prism volume (ft^3)	local residence time (days)
Present conditions	727,800	125,200	3.0
Alternative F1	618,300	232,800	1.3
Alternative F2	596,000	358,600	0.9

V.6.3 Environmental Effects of Flushing Improvement Strategies

Concerns may arise regarding the potential of increased saltwater intrusion associated with enhancing tidal exchange to Muddy and Frost Fish Creeks. However, tidal embayments with poor tidal flushing characteristics generally have a mean tide level higher than the embayments closer to the ocean. For example, the mean tide level in the Atlantic Ocean offshore of Chatham is between 0.0 and 0.5 feet above NGVD, the mean tide level in Pleasant Bay is approximately 1.7 feet NGVD, and the mean tide level in Muddy Creek is about 2.5 feet NGVD. The hydrology of the estuarine system requires a sloping surface, with the highest long-term mean water level in the upper portions of the estuary and the lowest mean water levels in the ocean. For estuarine systems exhibiting little tidal attenuation, the change in mean water level through the system generally is small. As Figures V-65, V-66and V-67 indicate, the mean tide level is similar or lower than the existing mean tide level for each alternative.

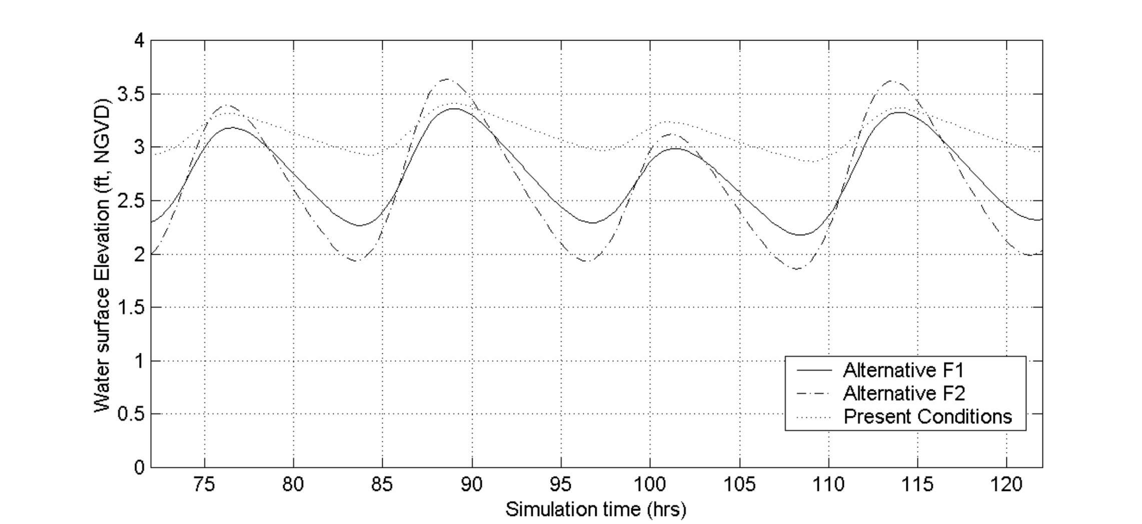

Figure V-67. Modeled tide range for Alternatives F1 and F2 compared with present conditions.

Due to the substantial tidal attenuation caused by the existing Frost Fish Creek culverts, the high tide level for the alternatives also remains similar to the existing high tide level. Only an increase in mean tide level will cause a measurable alteration to saltwater intrusion; therefore, the proposed tidal flushing improvements will have no negative impacts related to increased saltwater intrusion.

Creation of a freshwater system within Muddy Creek will enhance nitrogen attenuation. Since freshwater ponds and/or wetlands are often incorporated into nitrogen "removal" strategies, conversion of a portion of Muddy Creek to a freshwater system will provide two water quality improvement mechanisms: tidal exchange will be enhanced and the freshwater portion will provide natural attenuation of nitrogen. Prior to adopting this alternative for Muddy Creek, an evaluation of impacts to the brackish upper estuary needs to be performed. In addition, the future water quality modeling will analyze the improvements to total nitrogen concentrations that can be anticipated for each alternative.

V.7. SUMMARY

V.7.1 Conclusions

Tidal flushing of estuarine systems within the Stage Harbor System, the South Coast Embayments, and Pleasant Bay Region was evaluated using field measurements (Section V.3) and a calibrated hydrodynamic computer model (Section V.4). Field data included measured tides at eleven (11) locations, detailed depth measurements to augment previous bathymetric survey information, and current measurements taken along cross-channel transects. Field measurements of offshore tides in Pleasant Bay and Nantucket Sound, as well as depth measurements throughout the estuarine systems, provided input data to the computer models. Tide data collected within each sub-embayment were used to confirm the accuracy of the model simulations. For the Bassing Harbor and Stage Harbor systems, current measurements were used to verify the models calibrated with tide data. The computer model simulated water circulation in the estuary, including tides and currents. Two-dimensional current patterns, and water surface elevation were simulated by the model every twelve (12) minutes at thousands of points within each estuarine system. The modeled tides and currents were used to evaluate tidal flushing based on residence times and tidal circulation patterns.

A computer model was developed to simulate accurate tidal hydrodynamics in the Stage Harbor and Pleasant Bay Regions. The accuracy of model simulations was calibrated and verified by comparison to field data. The calibrated model provides a diagnostic tool for future analyses of water quality.

Based on the *local* residence time predictions alone, all of the embayments studied as part of the Stage Harbor system and South Coast Embayments (Stage Harbor, Sulphur Springs, and Taylors Pond) may be considered rapidly flushing systems. The rapid flushing rate of each system typically is an indicator of good relative water quality; however, each system has sub-embayments that exhibit signs of ecological stress, indicative of poor water quality. Therefore, the levels of nutrient loading likely controls water quality within the embayments (especially the upper portions of each system) to a greater degree than the hydrodynamic characteristics of each pond. In addition, it may be more appropriate to utilize *system* residence times to indicate estuarine health in the upper sub-embayments (e.g. Little Mill Pond), since the sub-embayments supplying these upper regions may have relatively poor water quality. For example, Little Mill Pond is flushed by waters traveling through Mill Pond, which exhibits signs of ecological stress.

Based on the *local* residence time predictions alone, much of the Bassing Harbor system may be considered rapidly flushing. Again, the rapid flushing rate of each system typically is an indicator of good relative water quality. The exception to the general rapid flushing of the Bassing Harbor system is Upper Frost Fish Creek (upstream of the Route 28 culverts). Substantial tidal attenuation occurs as a result of the flow restriction caused by under-sized culverts.

Similar to Upper Frost Fish Creek, Muddy Creek also shows substantial tidal attenuation as a result of the flow restriction created by culverts under Route 28. Although the Muddy Creek culverts are significantly larger than the Frost Fish Creek culverts, the greater surface area of the Muddy Creek estuarine system demands a much larger volume of water to raise the water level within the estuary.

The models were used to compute system and local residence times for existing conditions (Table V-12) in each estuarine system. Although tidal amplitude damping was greater across the Bucks Creek and Mill Creek systems than the Stage Harbor system, the limited water depth of these marsh-dominated estuaries (Bucks and Mill Creeks) produced lower overall residence times. Local residence times for the Pleasant Bay Region estuaries were similar to the Stage Harbor Region estuaries, with the exception of Muddy Creek and Frost Fish Creek. Local residence times for Muddy and Frost Fish Creeks (3.0 days for each) indicated reduced flushing for these areas.

Analysis of two-dimensional current patterns revealed that maximum currents within each estuary occurred within the inlets. For example, maximum flood currents were approximately 3.3 and 3.2 feet per second for the Stage Harbor and Bassing Harbor entrances, respectively.

Due to the rapidly changing geomorphology of the Chatham Harbor/Pleasant Bay entrance (New Inlet), a “worst-case” flushing analysis was performed utilizing historic pre-breach morphology and bathymetry. This analysis indicated that residence times would increase between 10 and 88 percent as the system returns to its pre-breach form.

The analysis of alternatives to improve tidal flushing in Frost Fish and Muddy Creeks indicated that a variety of options are available to dramatically improve tidal exchange through the Route 28 culverts. For Muddy Creek, placement of a dike at the approximate mid-point of the system (Figure V-64) would convert the upper half of the system into freshwater. Reduction in the surface area of the tidal portion would reduce the residence time by approximately 50%. Other options for Muddy Creek include increasing the size of the culverts and conversion of the entire estuary to a freshwater system. A modest increase in culvert size at Frost Fish Creek would more than double the tidal exchange. For both Muddy and Frost Fish Creeks, a more complete analysis of environmental impacts associated with improved tidal flushing should be performed prior to implementing project design.